

NEW RESULTS FROM MINOS

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OUTLINE



- Overview of Oscillations and MINOS
- Results from the Full Run
 - Muon Neutrino and Antineutrino Disappearance Results
 - Electron Neutrino Appearance Results
 - Neutrino Time of Flight Measurement
- The future and MINOS+



NEUTRINOS HAVE MASS!



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
 - Flavor States: creation and detection
 - Mass States: propagation

- A neutrino created as one flavor can later be detected as another flavor, depending on:
 - distance traveled (L)
 - neutrino energy (E)
 - difference in the squared masses ($\Delta m_{ij}^2 = m_i^2 - m_j^2$)
 - The mixing amplitudes ($U_{\alpha j}$)



THE PMNS MIXING MATRIX

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- (12) Sector: reactor + solar, L/E~15,000 km/GeV

$${}^{\dagger} \Delta m_{21}^2 = 7.50_{-0.20}^{+0.19} \times 10^{-5} \text{ eV}^2 \quad \tan^2 \theta_{12} = 0.452_{-0.033}^{+0.035}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$${}^{\ddagger\dagger} |\Delta m_{32}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{ eV}^2 \quad {}^* \sin^2(2\theta_{23}) > 0.96 \text{ (90% C.L.)}$$

- (13) Sector: reactor and accelerator, L/E~500 km/GeV

$${}^{**} \sin^2(2\theta_{13}) = 0.089 \pm 0.010 \text{ (stat.)} \pm 0.005 \text{ (syst.)}$$

[†]PRD 83.052002(2011)

^{‡‡}PRL 106. 181801(2011)

^{*}SuperK Preliminary, Nu2010

^{**}Daya Bay Preliminary, Nu2012

WHY MEASURE ALL THESE ANGLES?



- Precision measurements provide a valuable check that neutrino oscillations are the solution to neutrino anomalies
- PMNS matrix analogous to CKM matrix
 - lepton sector mixing much larger than quark sector mixing
 - Is there CP violation in the lepton sector?
 - Is it big enough to account for matter vs. antimatter asymmetry in the Universe?
- Small neutrino mass suggests a heavy partner (see-saw mechanism)—Neutrinos provide a window to physics at the GUT scale!





THE MINOS EXPERIMENT



Far Detector
735 km from Source

- Two detectors mitigate systematic effects
 - beam flux mis-modeling
 - neutrino interaction uncertainties



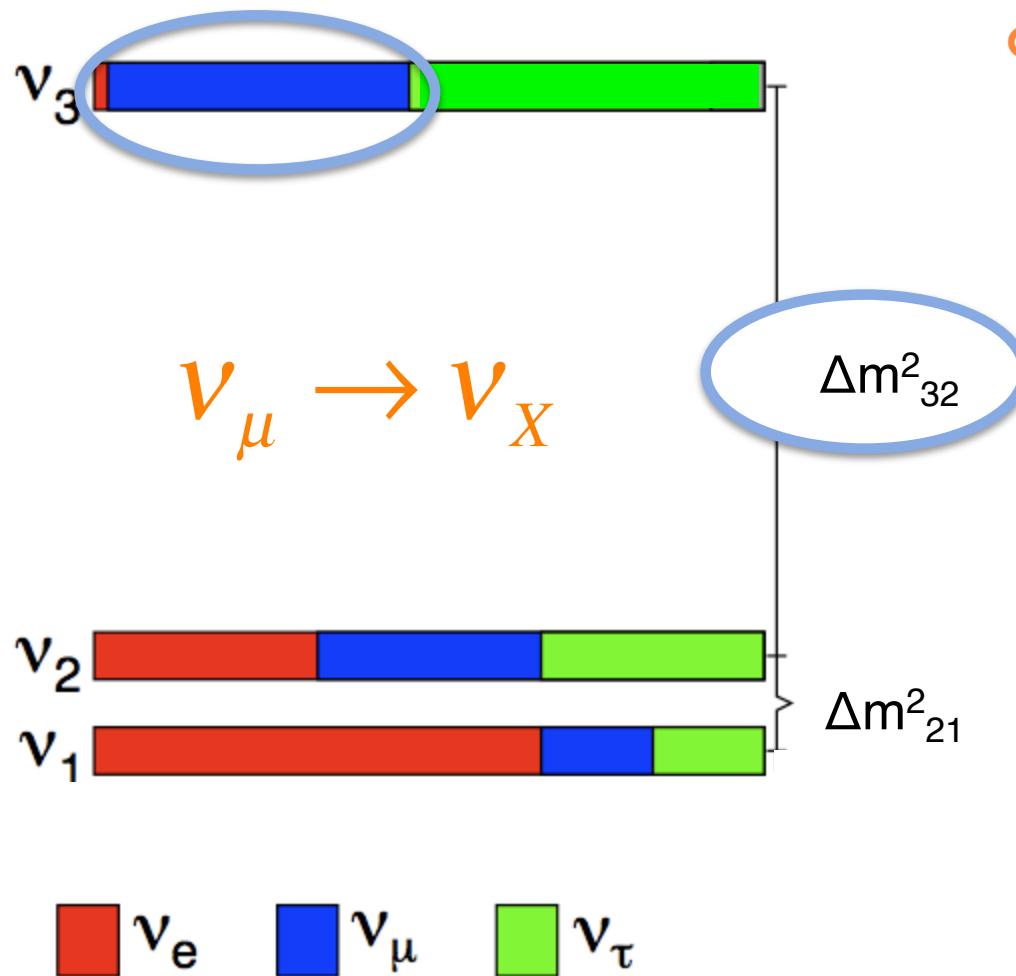
- Long-baseline neutrino oscillation experiment
- Neutrinos from NuMI beam line
- $L/E \sim 500 \text{ km/GeV}$
- atmospheric Δm^2



Near Detector
1 km from Source



MINOS PHYSICS GOALS

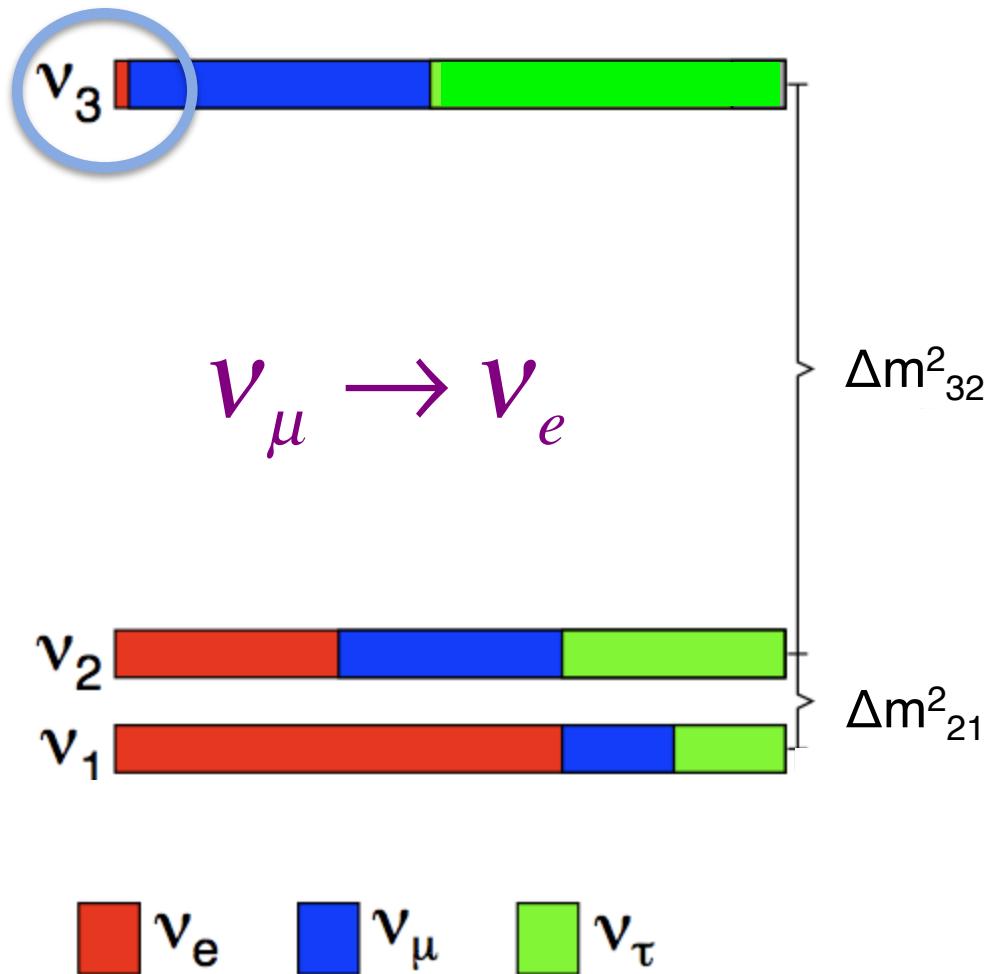


- Measure v_μ disappearance as a function of energy

- Δm^2_{32} and $\sin^2(2\theta_{23})$
- test oscillations vs. alternatives
- look for differences between neutrino and anti-neutrinos



MINOS PHYSICS GOALS



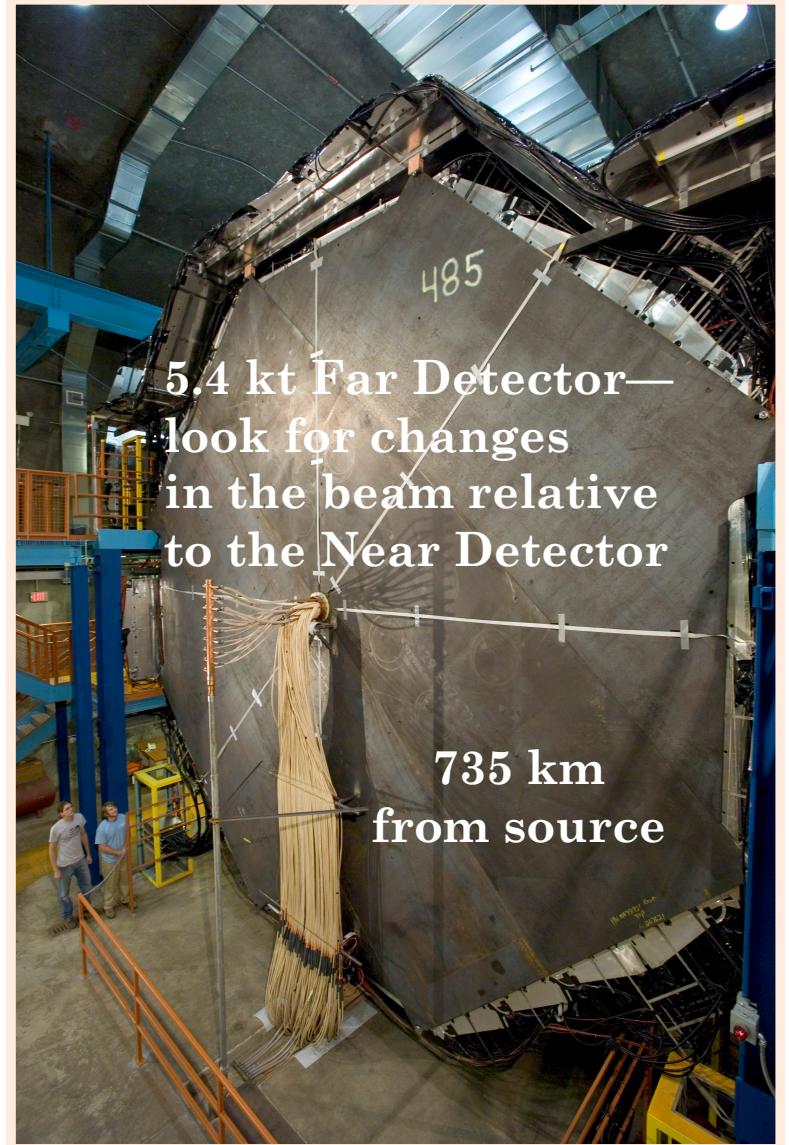
- Measure ν_μ disappearance as a function of energy
 - Δm^2_{32} and $\sin^2(2\theta_{23})$
 - test oscillations vs. alternatives
 - look for differences between neutrino and antineutrinos
- Study $\nu_\mu \rightarrow \nu_e$ **mixing**
 - measure θ_{13}
 - δ_{CP}
 - mass hierarchy



THE DETECTORS

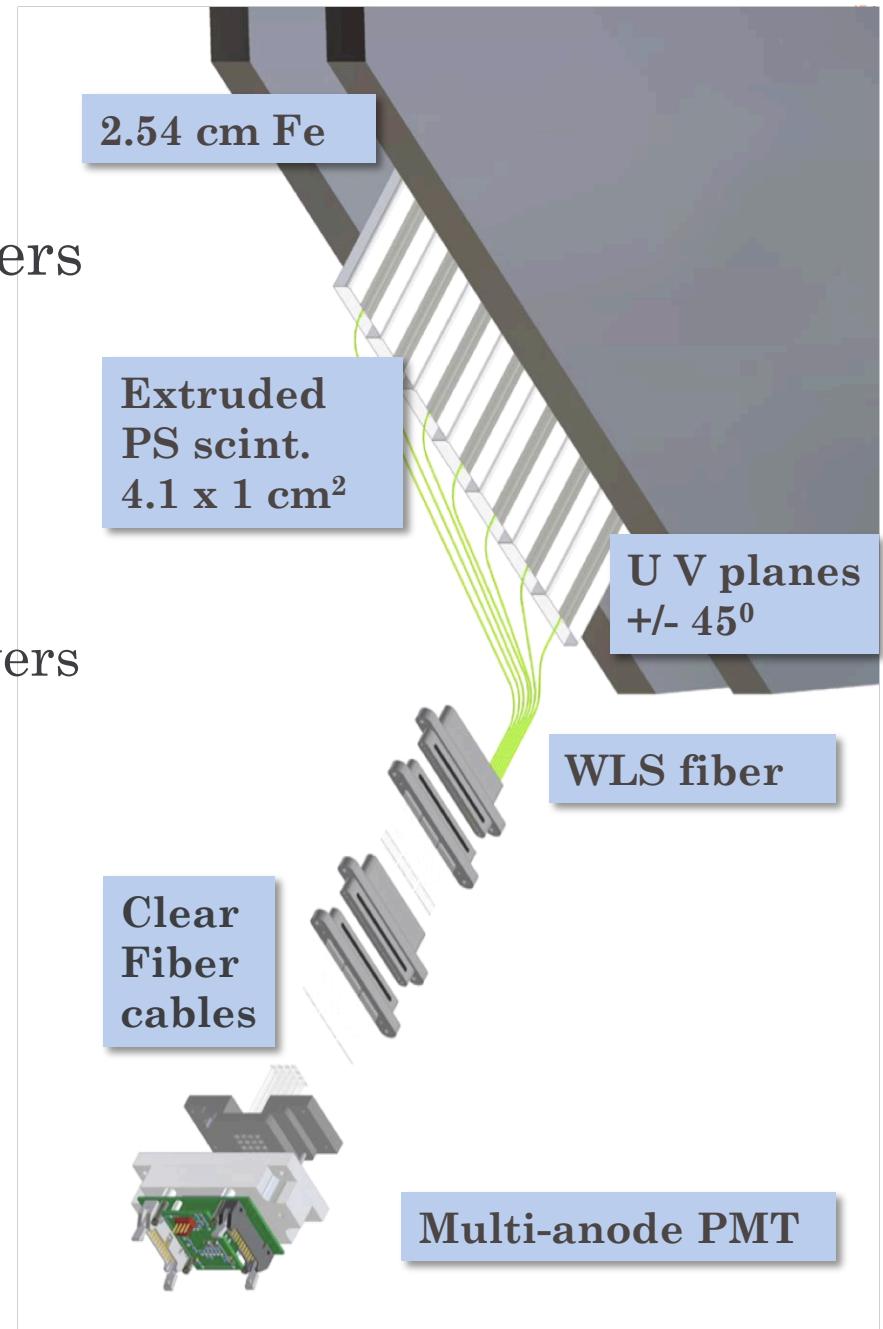
FD running since 2003

ND running since 2005

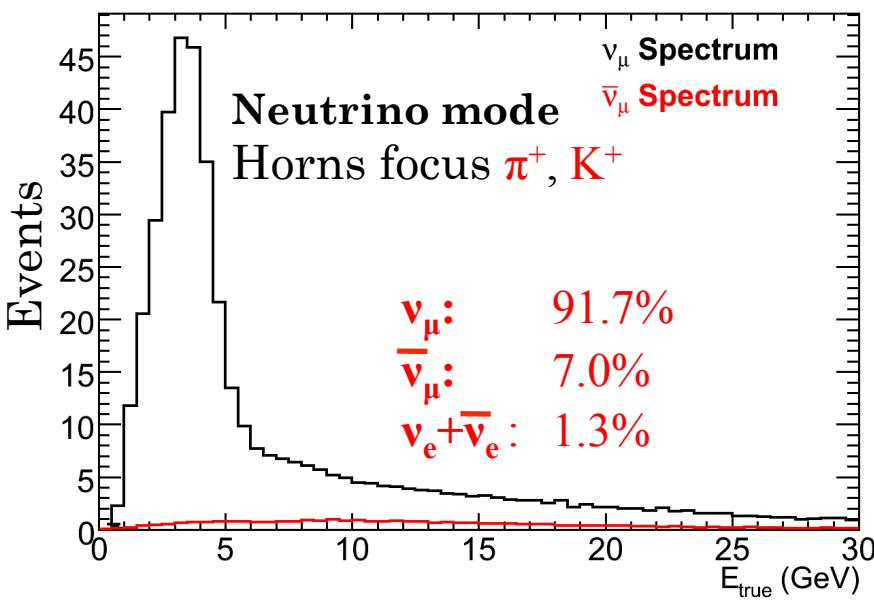
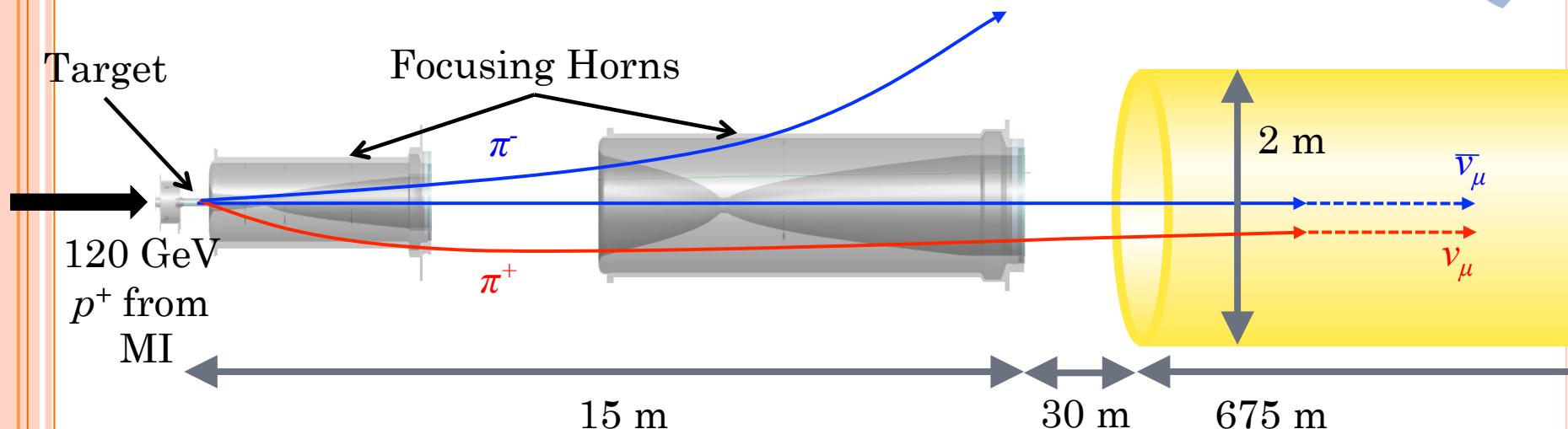


DETECTOR TECHNOLOGY

- Tracking sampling calorimeters
 - steel absorber 2.54 cm thick ($1.4 X_0$)
 - scintillator strips 4.1 cm wide (1.1 Moliere radii)
 - 1 GeV muons penetrate 28 layers
- Magnetized
 - muon energy from range/curvature
 - distinguish μ^+ from μ^-
- Functionally equivalent
 - same segmentation
 - same materials
 - same mean B field (1.3 T)

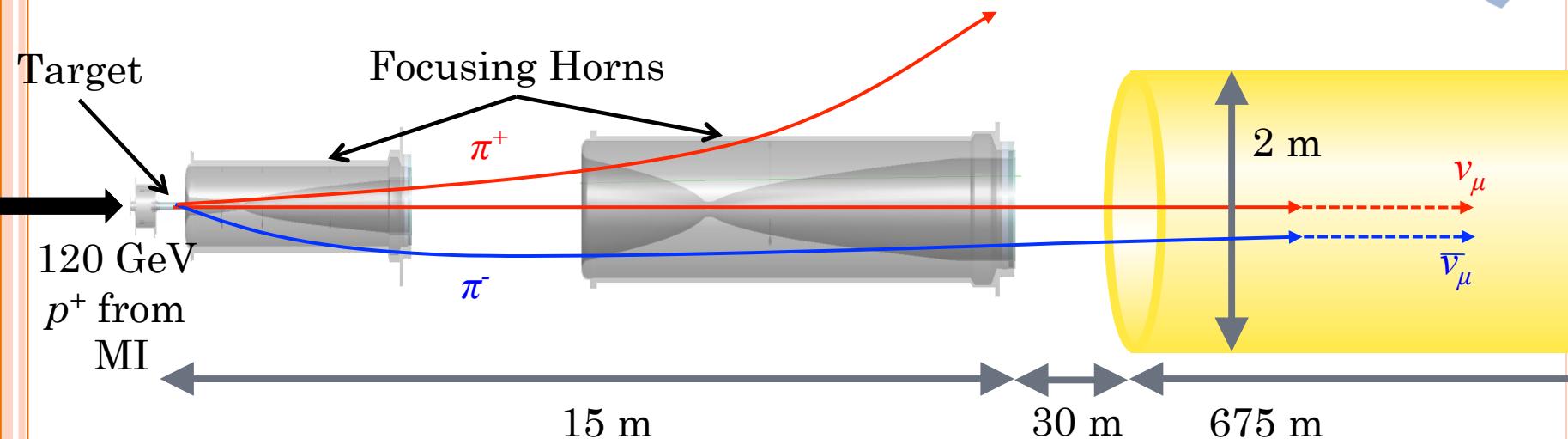


MAKING A NEUTRINO BEAM

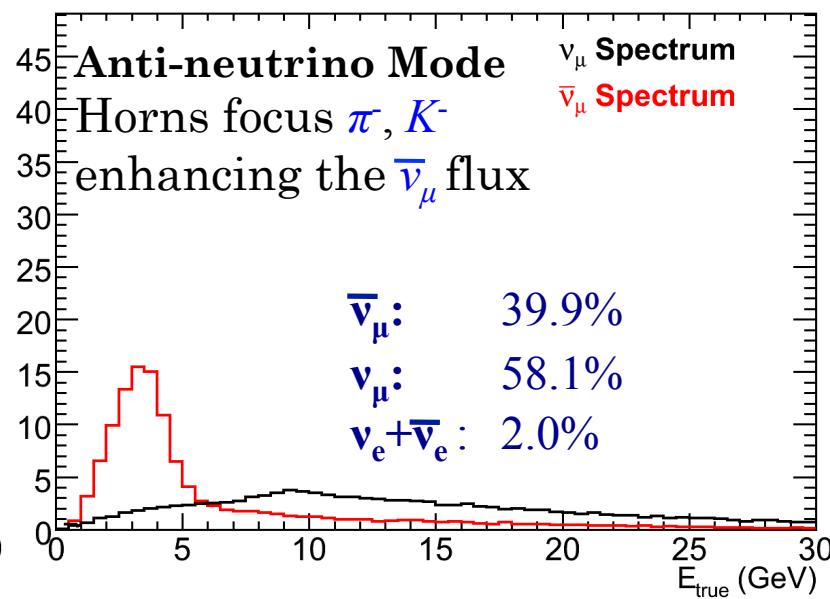
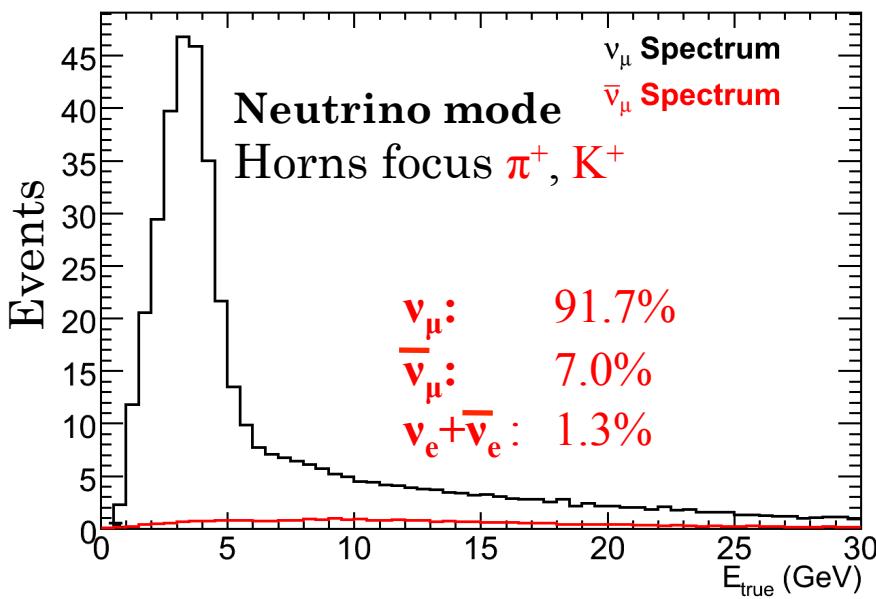


- **Production:** bombard graphite target with 120 GeV p^+
 - 2 interaction lengths
 - 340 kW typical power
- **Focusing:** 2 magnetic focusing horns
 - sign selected hadrons
 - energy of focused particles depends on separation between target and horns
- **Decay:** 2 m diameter pipe
- **Result:** wide band neutrino beam

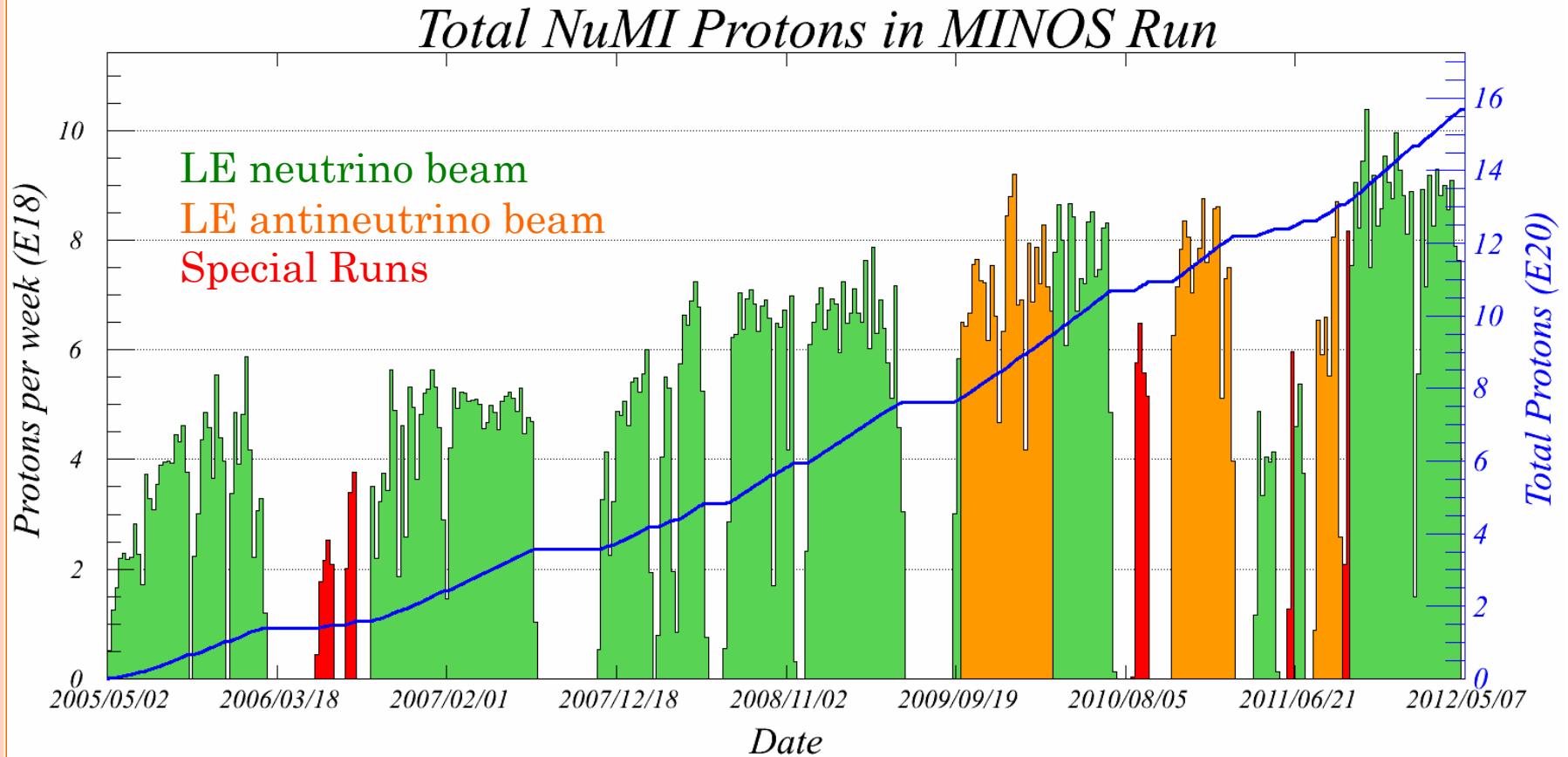
MAKING A NEUTRINO BEAM



P. Vahle, W&M June 2012



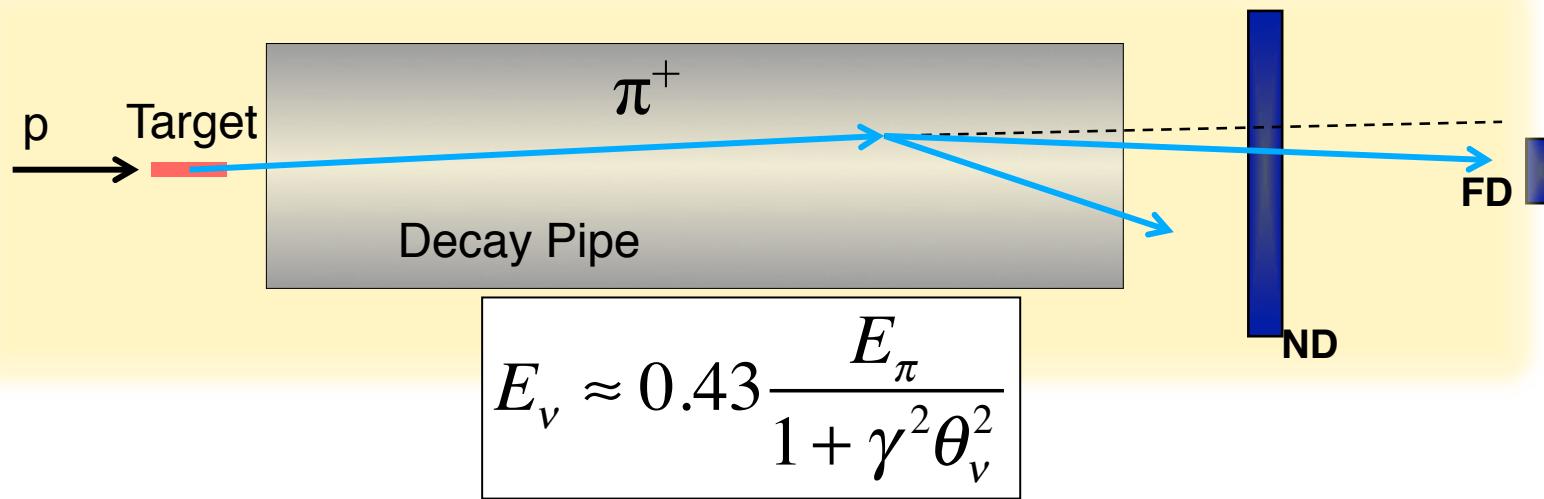
1.5 SEXTILLION POTs



- NuMI beam shut off April 30, 2012
- Accumulated more than 15×10^{20} POT
 - 10.7×10^{20} POT in (LE) neutrino running
 - 3.36×10^{20} POT in antineutrino running



Far spectrum without oscillations is similar, but
not identical to the Near spectrum!

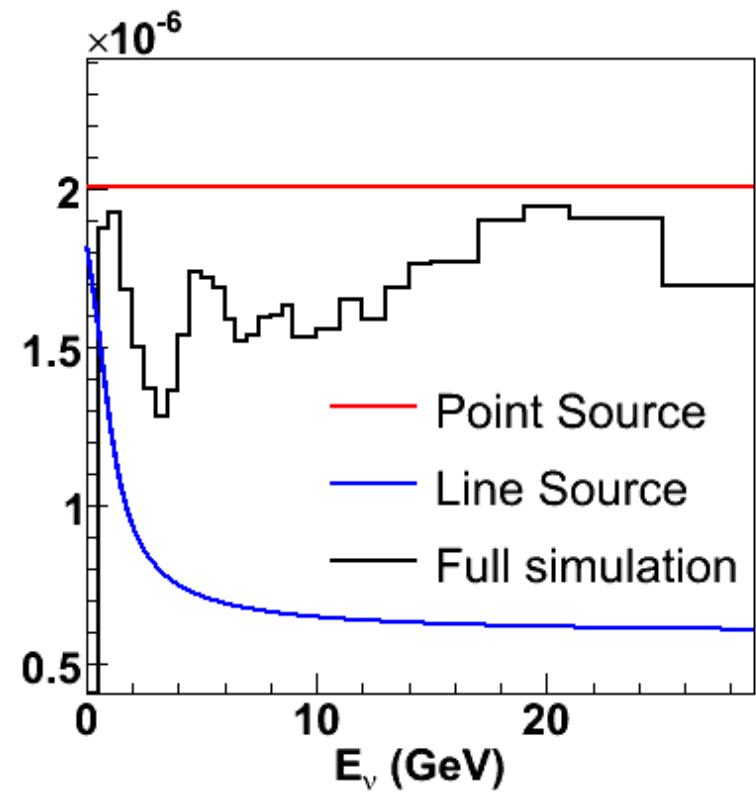
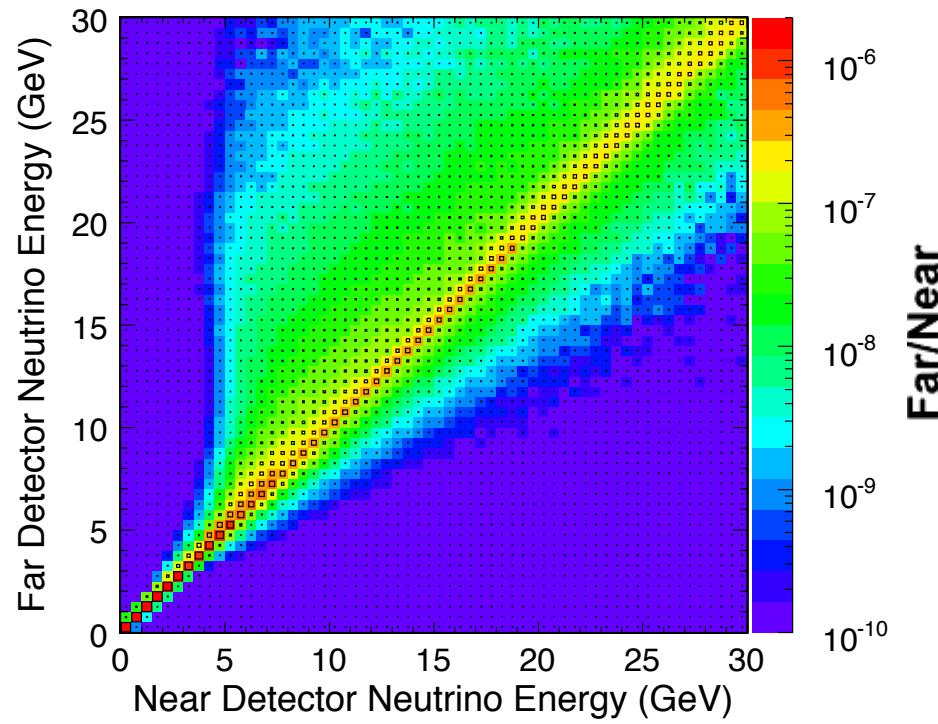


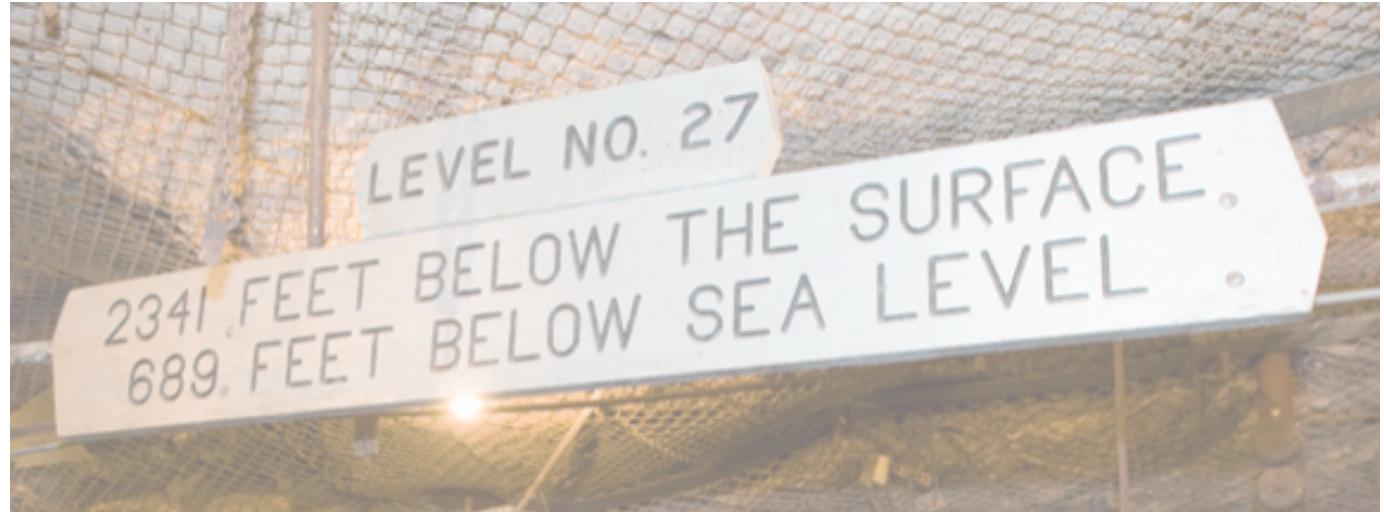
- Neutrino energy depends on angle wrt original pion direction and parent energy
 - angular distributions different between Near and Far
 - higher energy pions decay further along decay pipe



EXTRAPOLATION

- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- Electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





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MUON NEUTRINO DISAPPEARANCE



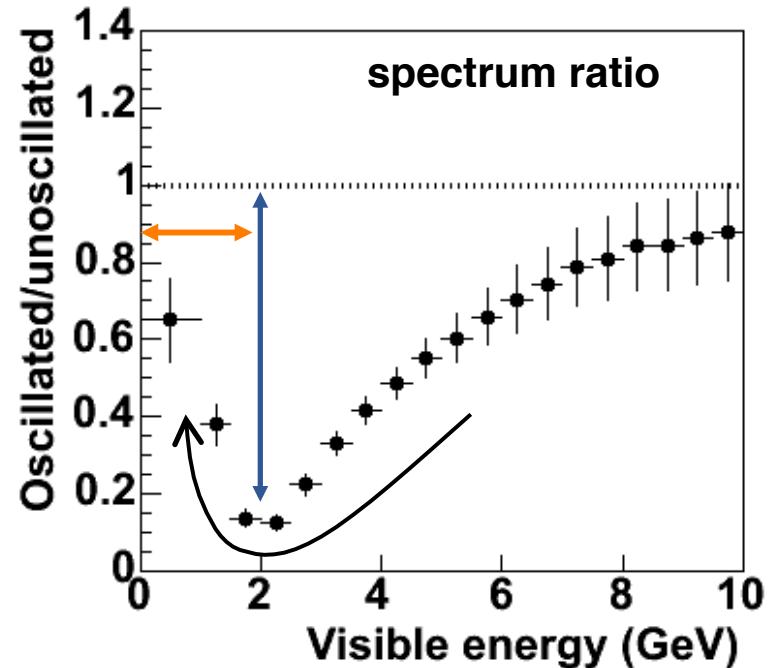
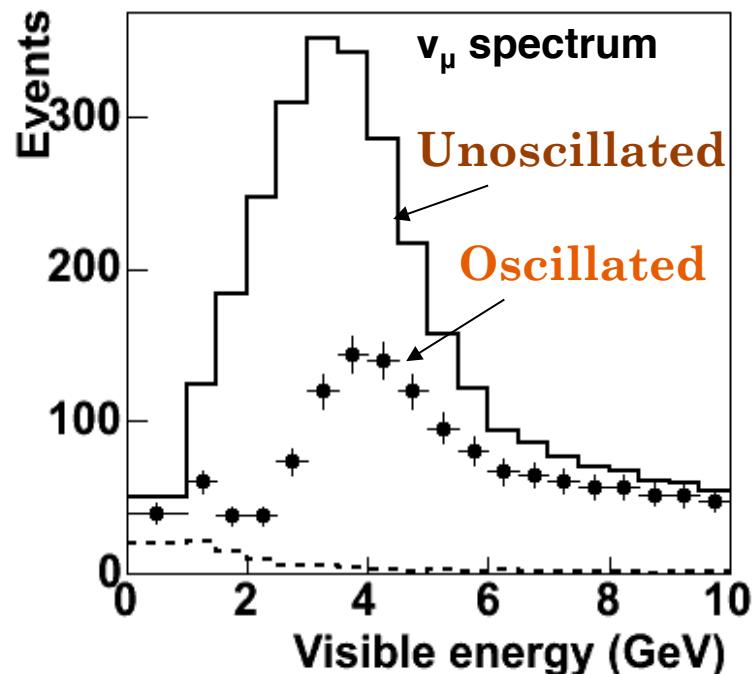
MUON NEUTRINO DISAPPEARANCE



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E)$$

Monte Carlo

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3} \text{ eV}^2$)



in limit where $\theta_{13} = 0$

$$\theta \approx \theta_{23} \quad |\Delta m^2| \approx \sin^2(2\theta_{12}) |\Delta m_{31}^2| + \cos^2(2\theta_{12}) |\Delta m_{32}^2|$$

Full 3 flavor analysis in the works

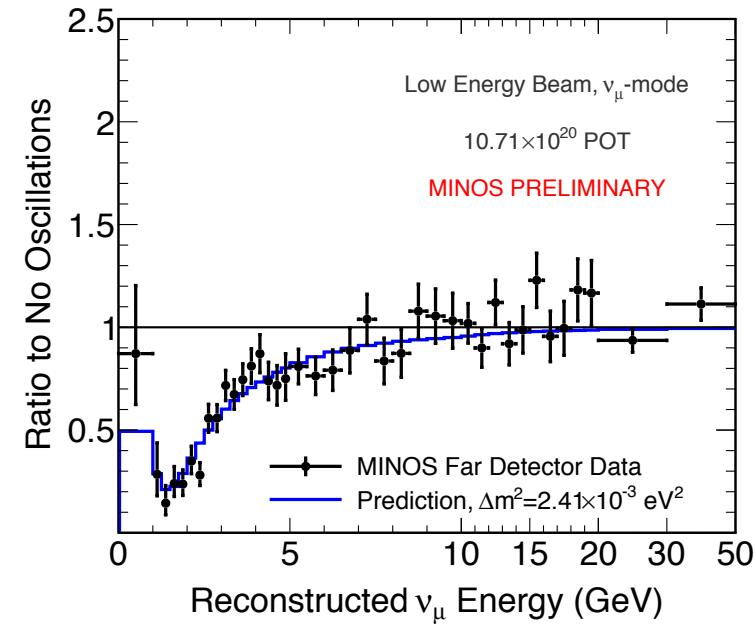
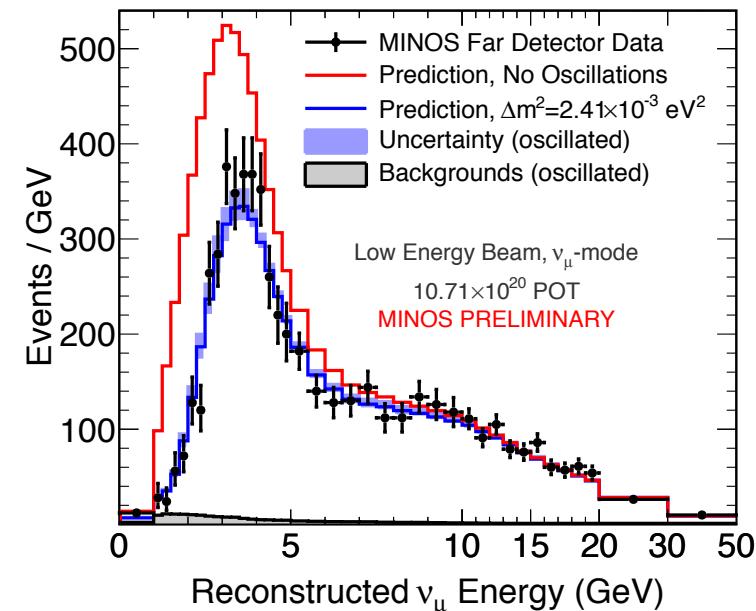
MUON NEUTRINO OSCILLATION RESULTS



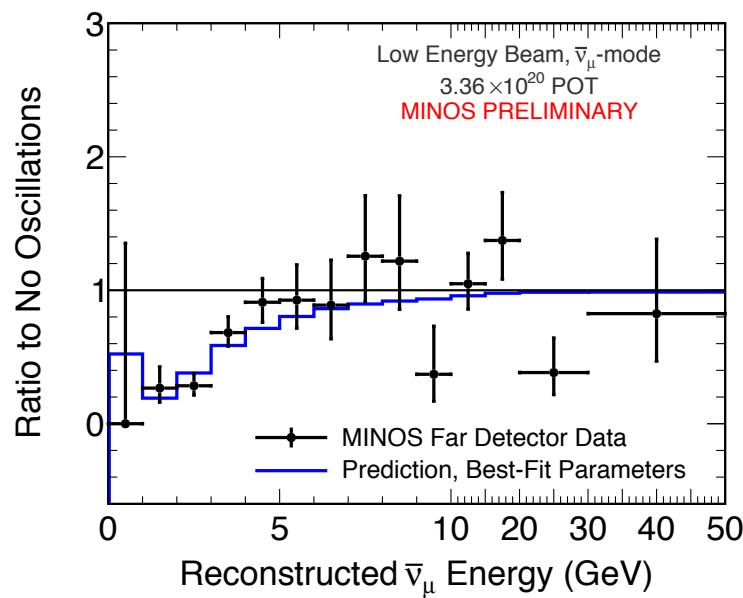
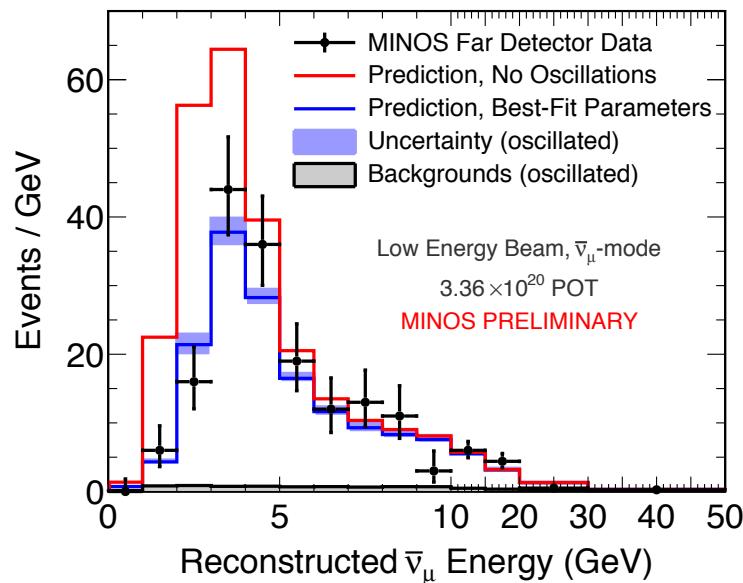
- No Oscillations: 3564
- Observed: 2894
- Best Fit:

$$|\Delta m^2| = 2.41^{+0.11}_{-0.10} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$



MUON ANTINEUTRINO OSCILLATION RESULTS



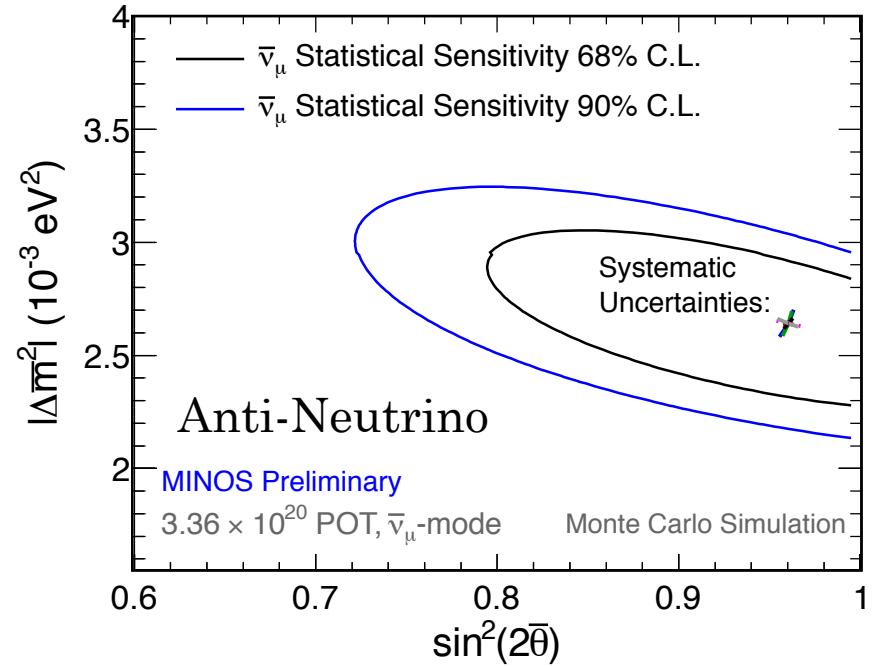
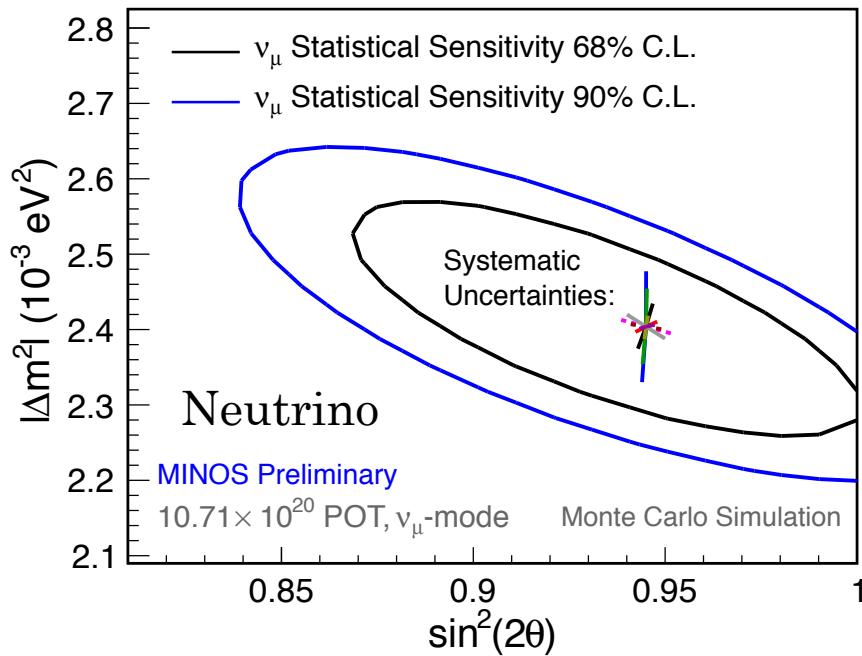
- No Oscillations: 312
- Observed: 226
- Best Fit:

$$|\Delta\bar{m}^2| = 2.64_{-0.27}^{+0.28} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.78 \text{ (90% C.L.)}$$



SYSTEMATICS

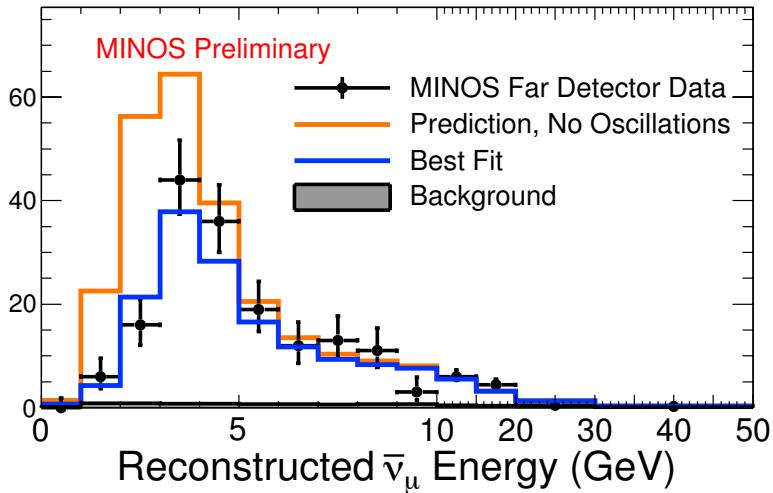


- Largest sources of systematic uncertainty:
 - Hadronic Energy Scale
 - Track Energy Scale
 - Neutral Current background
- Still statistics dominated in both modes

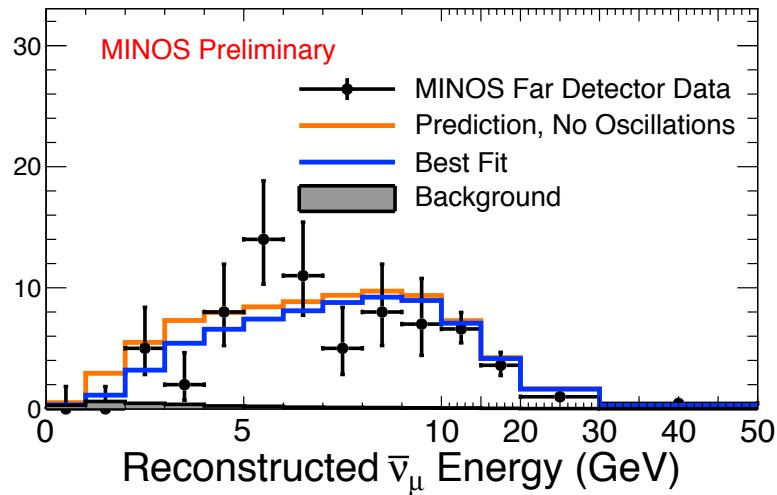


MORE ANTINEUTRINOS

Events / GeV



Events / GeV



- No Oscillations: 536
- Observed: 414

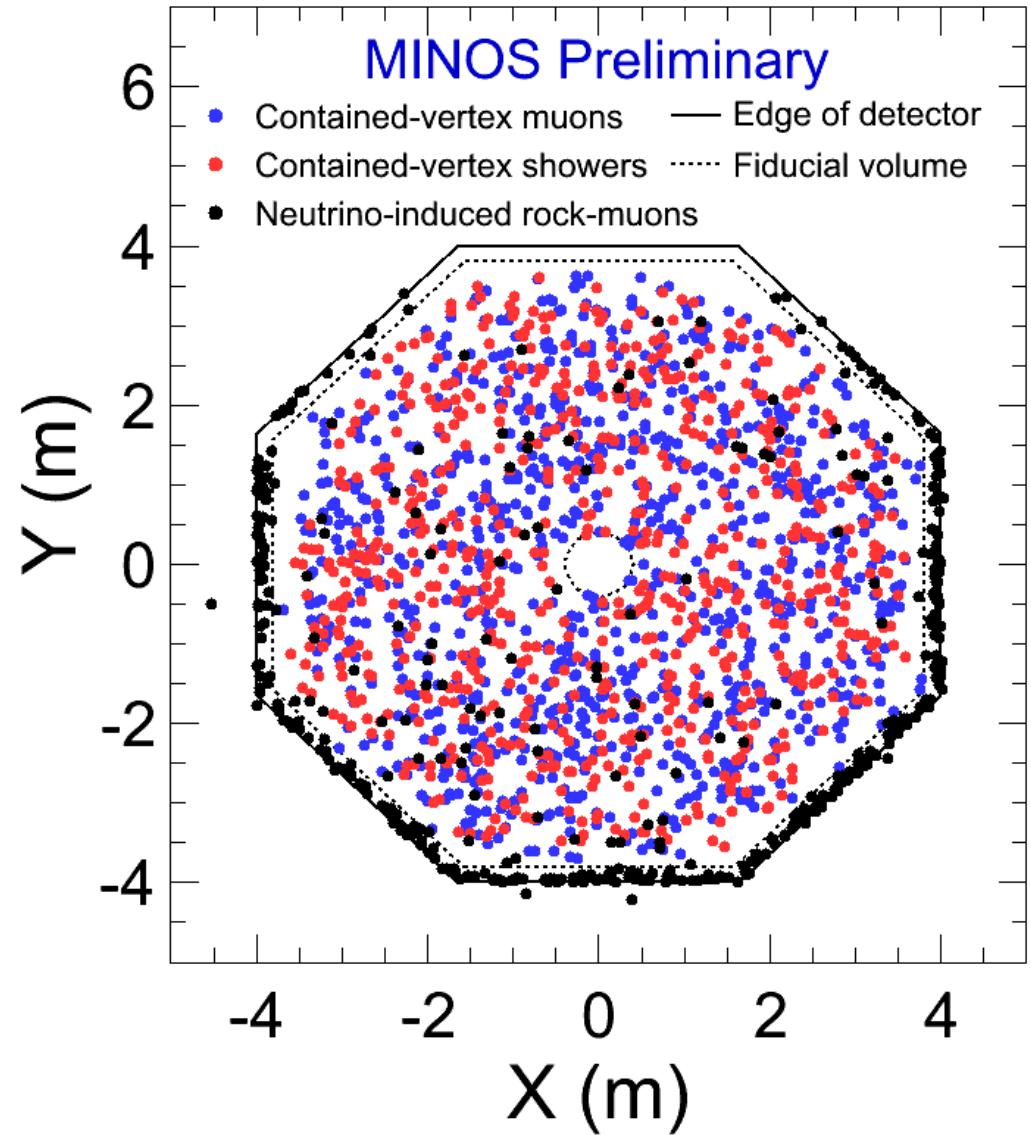
$$|\Delta\bar{m}^2| = 2.60_{-0.23}^{+0.28} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.80 \text{ (90\% C.L.)}$$

ATMOSPHERIC NEUTRINOS



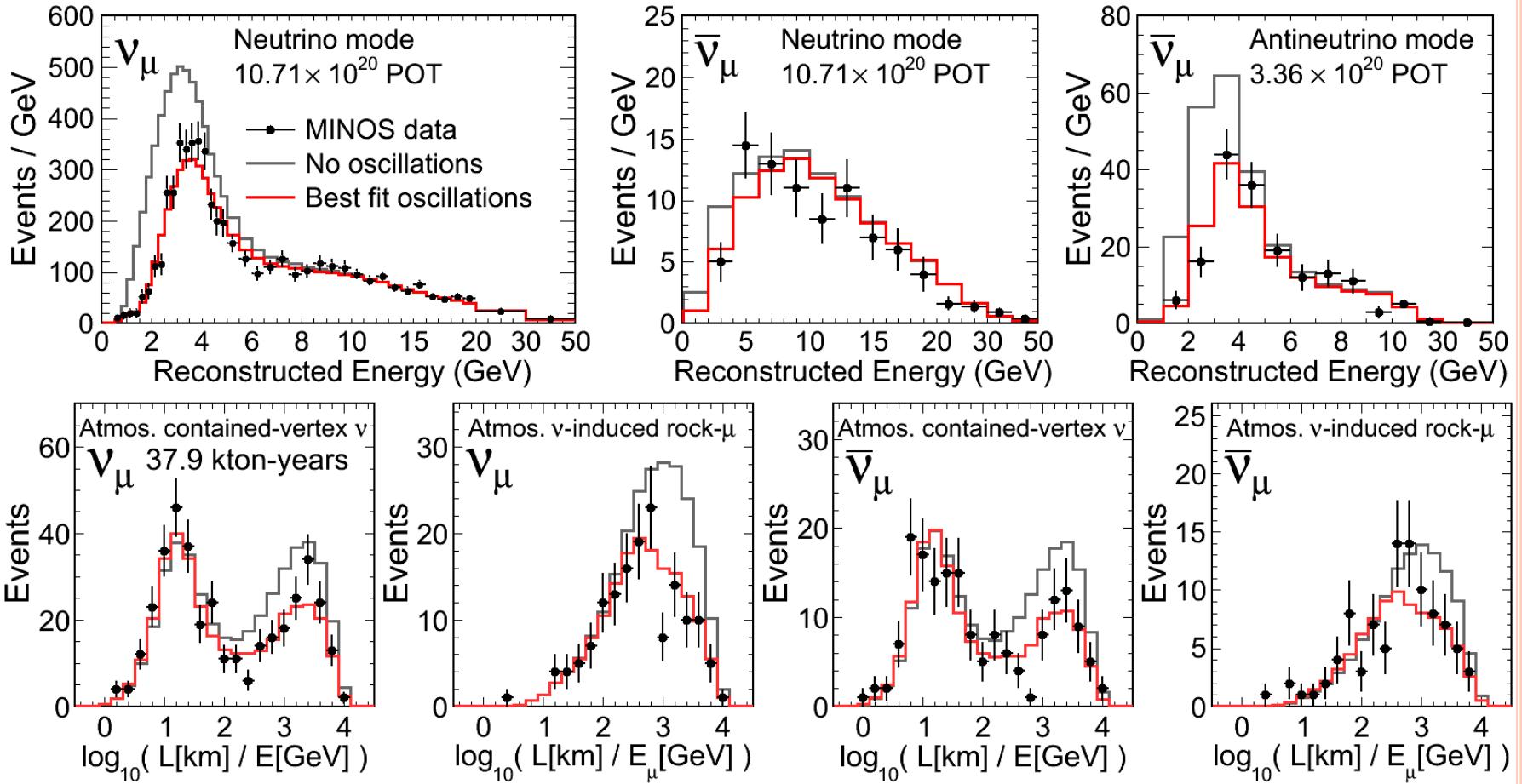
- 39.7 kton years of atmospheric neutrino data collected since 2003
- 2072 additional neutrino events
 - 905 contained vertex muon events
 - 466 neutrino induced rock muon events
 - 701 contained vertex showers



ATMOSPHERIC NEUTRINOS



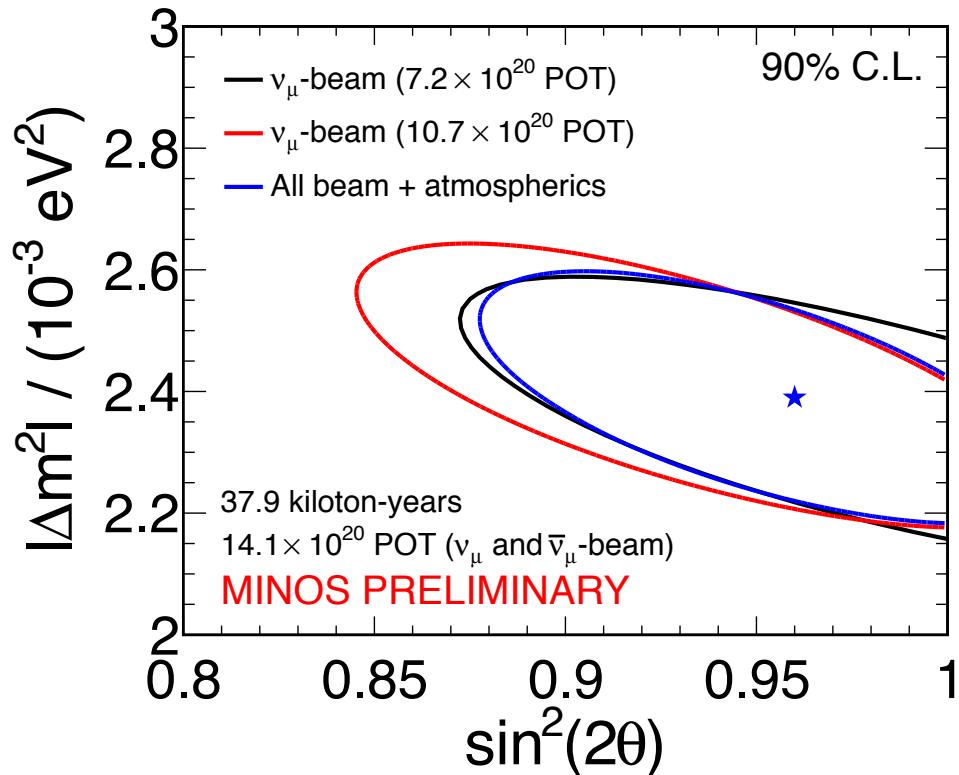
MINOS PRELIMINARY



- 15 sources of systematic uncertainty included as nuisance parameters
- Oscillations fit the data well: 64% of pseudo experiments have worse χ^2



COMBINED NEUTRINO CONTOURS



- Combined MINOS neutrino oscillation parameters:

$$|\Delta m^2| = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

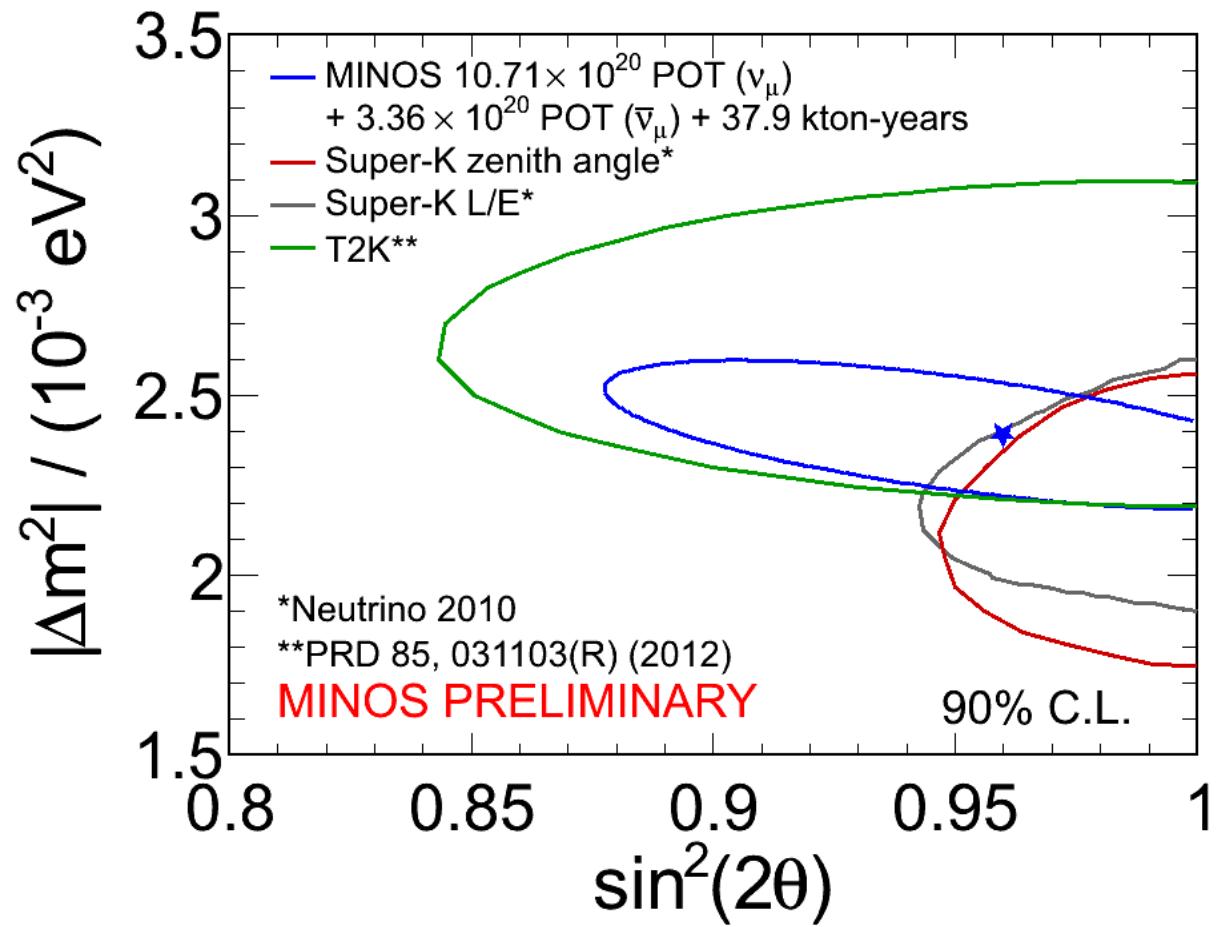
$$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ (90% C.L.)}$$

All beam and atmospheric samples in a two parameter fit
(assumes neutrinos and antineutrinos oscillate the same)



MINOS v. THE WORLD



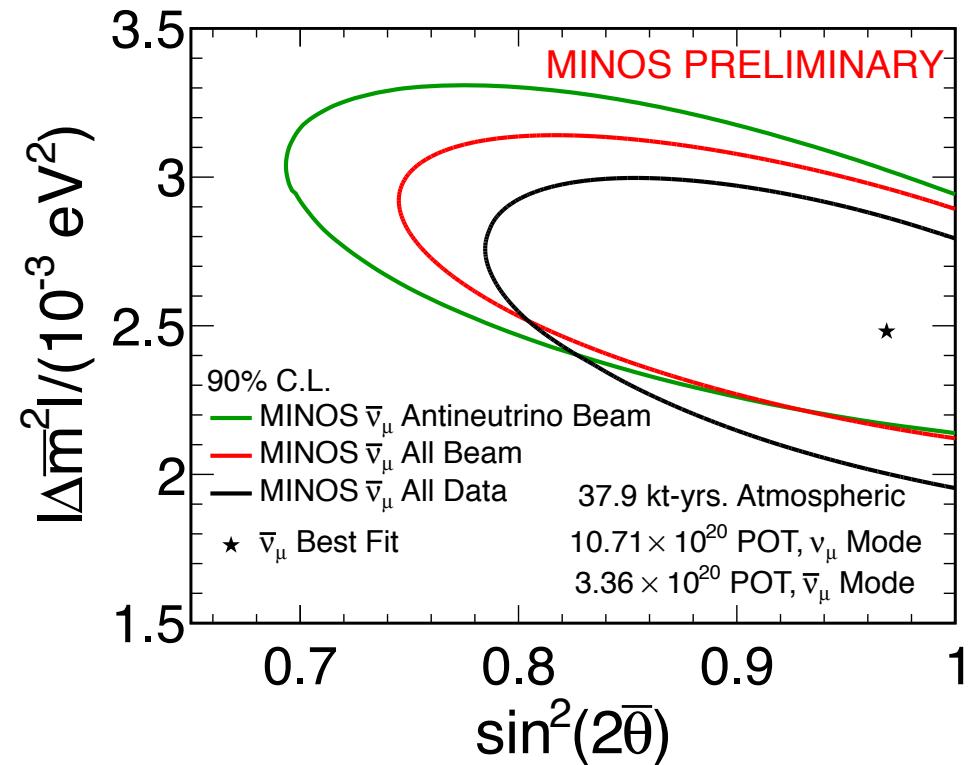
COMBINED ANTINEUTRINO CONTOURS



- Combined MINOS antineutrino oscillation parameters:

$$|\Delta\bar{m}^2| = 2.48^{+0.22}_{-0.27} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90% C.L.)}$$



All beam and atmospheric samples in a four parameter fit
(neutrinos and antineutrino are allowed to oscillate differently)

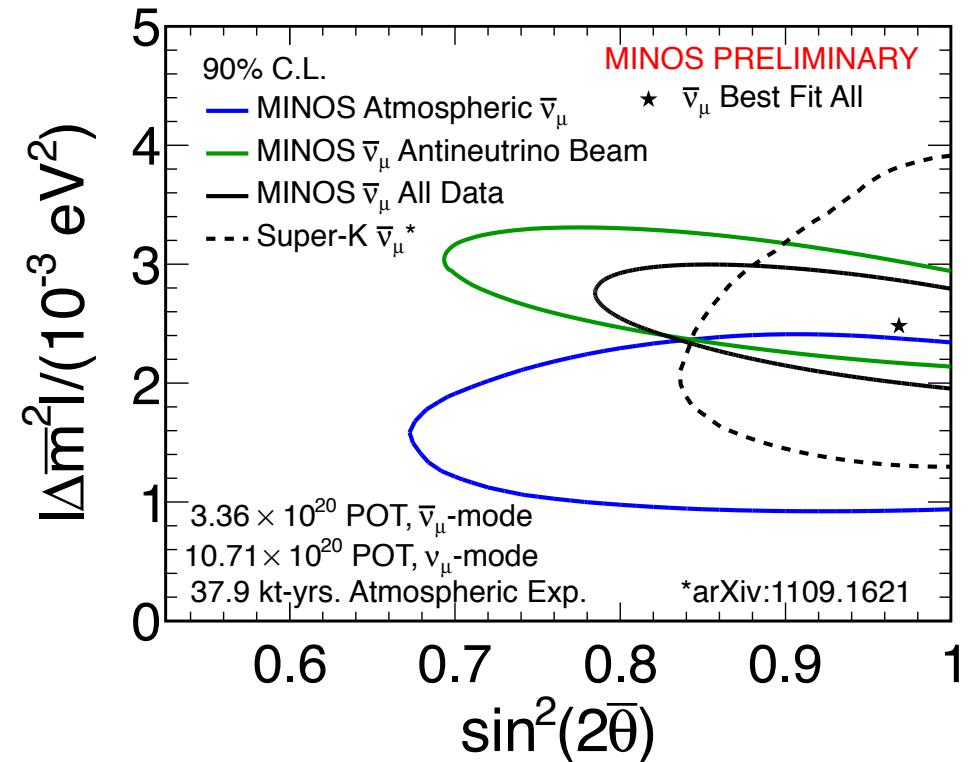
COMBINED ANTINEUTRINO CONTOURS



- Combined MINOS antineutrino oscillation parameters:

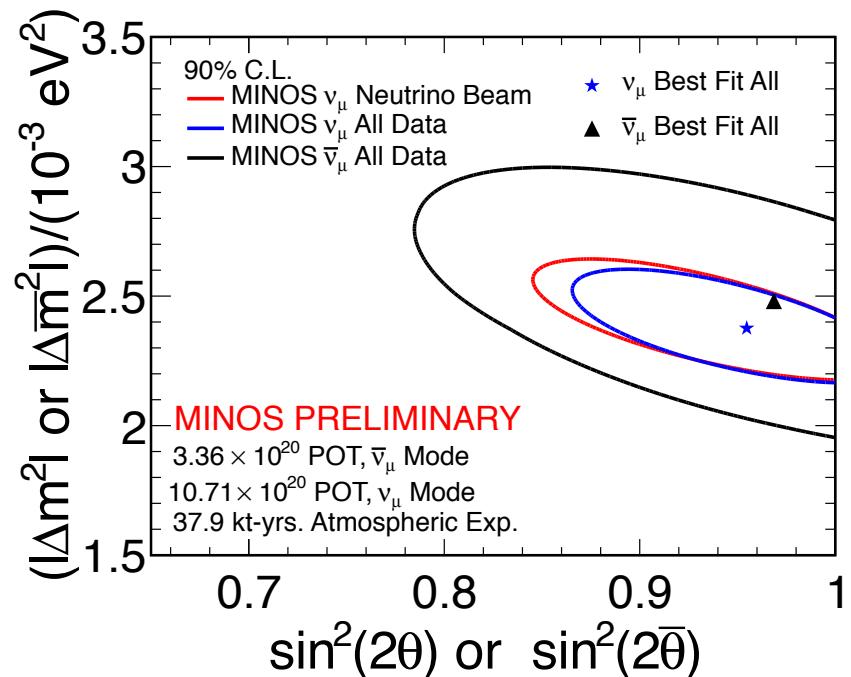
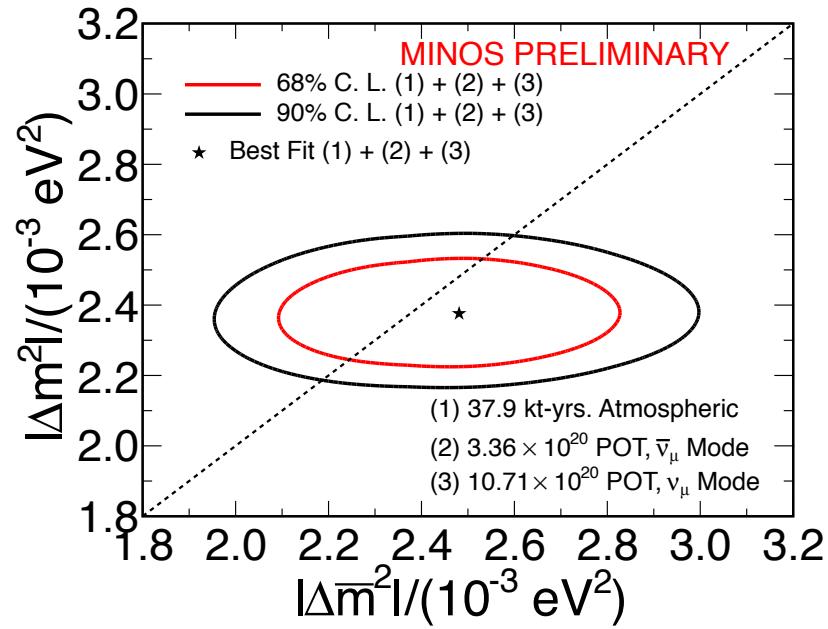
$$|\Delta\bar{m}^2| = 2.48^{+0.22}_{-0.27} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90% C.L.)}$$



All beam and atmospheric samples in a four parameter fit
(neutrinos and antineutrino are allowed to oscillate differently)

COMPARING NEUTRINOS AND ANTINEUTRINOS



$$|\Delta \bar{m}^2| - |\Delta m^2| = 1.0_{-2.8}^{+2.4} \times 10^{-4} \text{ eV}^2$$

New data has resolved tension between neutrino and antineutrino results



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ELECTRON NEUTRINO APPEARANCE





ELECTRON NEUTRINO APPEARANCE

- A few percent of the missing ν_μ could change into ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i\left(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$

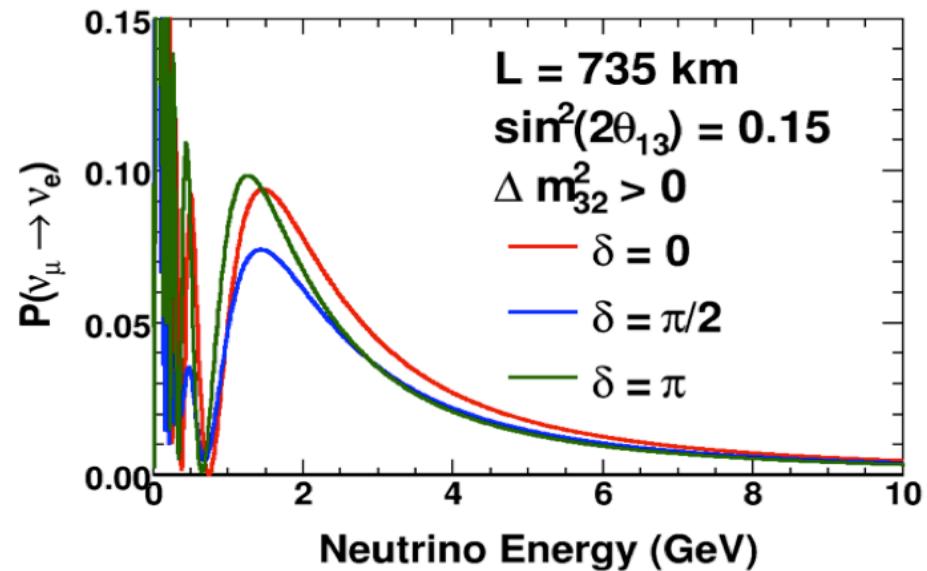
“Solar” Term
<1% in MINOS

Interference Term

- for neutrinos
- + for antineutrinos

if $\delta_{CP} \neq 0$,

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



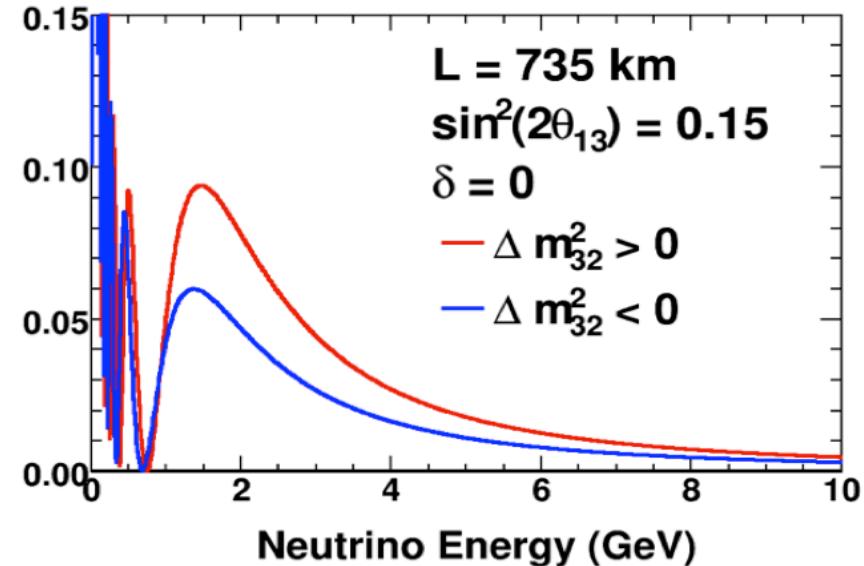
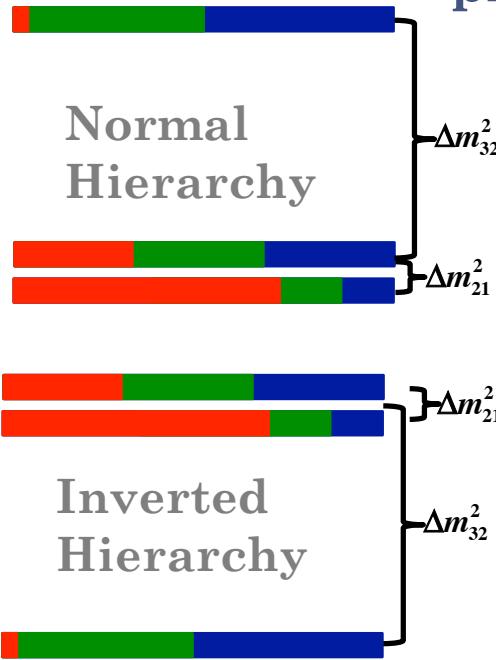


ELECTRON NEUTRINO APPEARANCE

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$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i(\frac{\Delta m_{32}^2 L}{4E} + \delta_{cp})} + \sqrt{P_{sol}} \right|^2$$

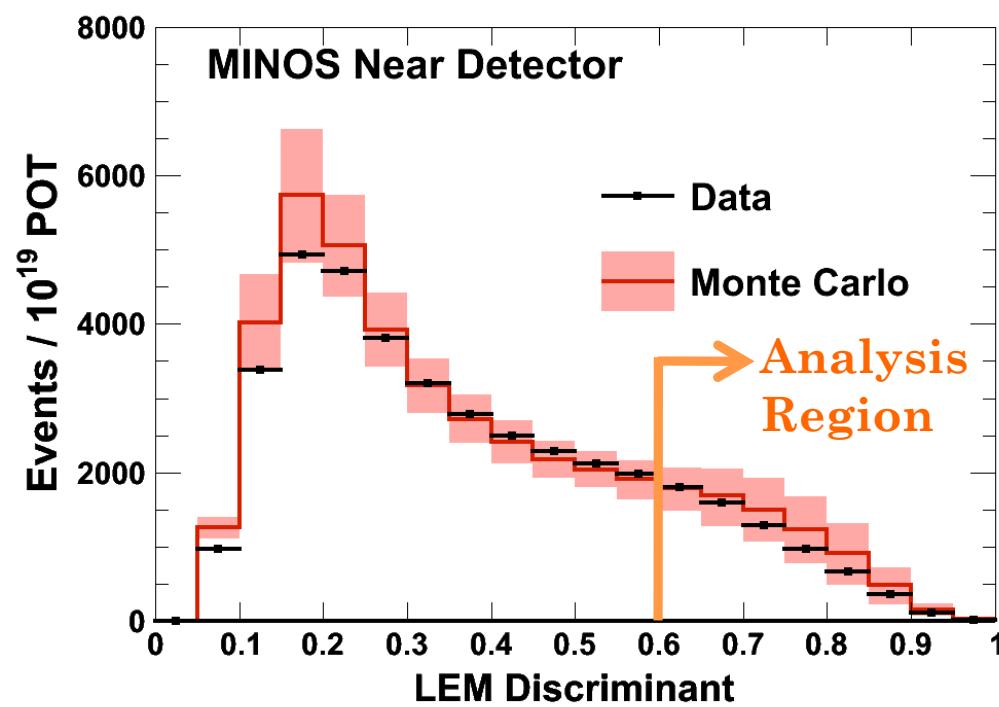
In matter, $\nu_e + e$ CC scattering modifies oscillation probability $\sim 30\%$ in MINOS





SELECTING ELECTRON NEUTRINOS

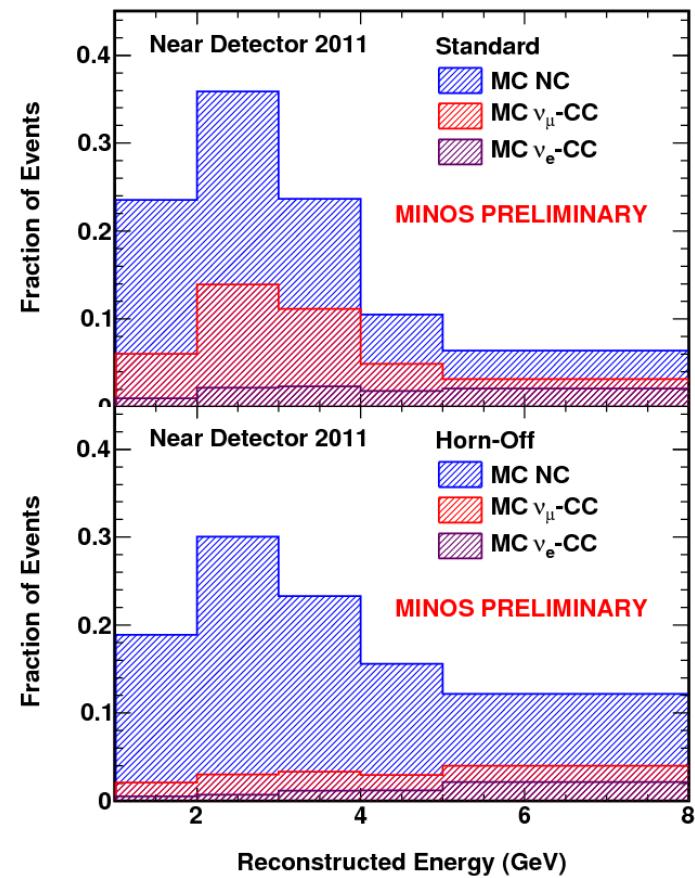
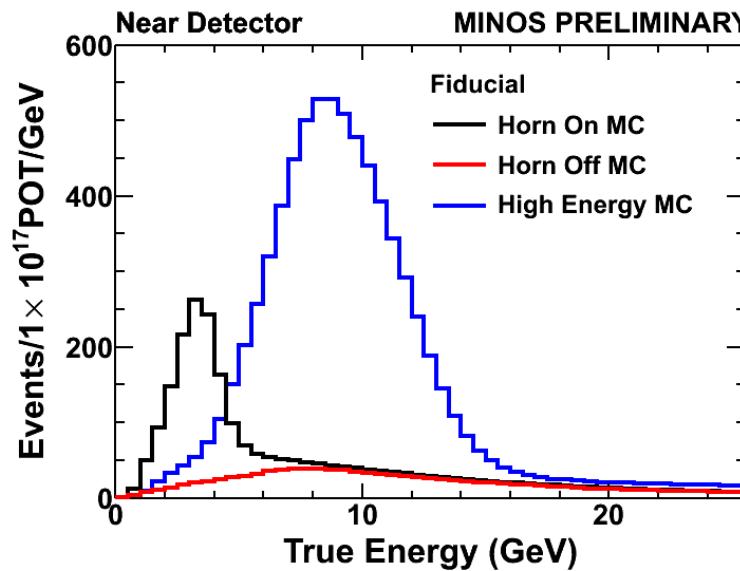
- Coarse detector granularity makes ν_e CC identification challenging
 - Compare candidate events, strip-by-strip, to a library of MC events
 - Compute discriminating variables based on truth information from library events that best match the candidate
- Apply selection to ND for background determination





ELECTRON NEUTRINO APPEARANCE

- Selected ND data comprised of NC, ν_μ CC, and beam ν_e events
- Each extrapolates to FD differently
- Use ND data in different configurations to extract relative components of background

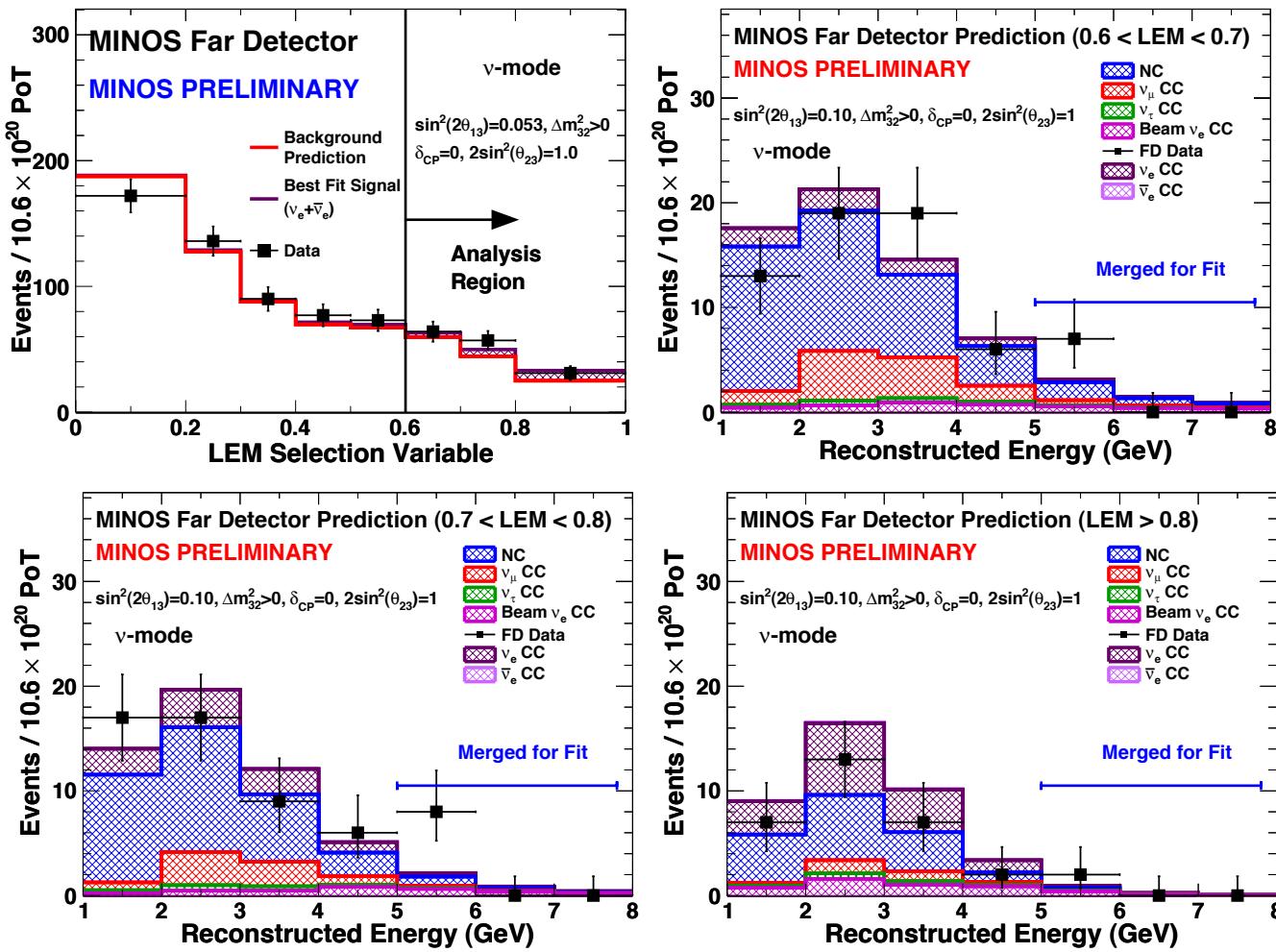




ELECTRON NEUTRINO APPEARANCE: FHC BEAM

In Signal Enhanced Region:

- If $\theta_{13}=0$: 69.1 BG Events
- If $\sin^2(2\theta_{13})=0.1$: +26.0 Events
- Observe: 88 Events

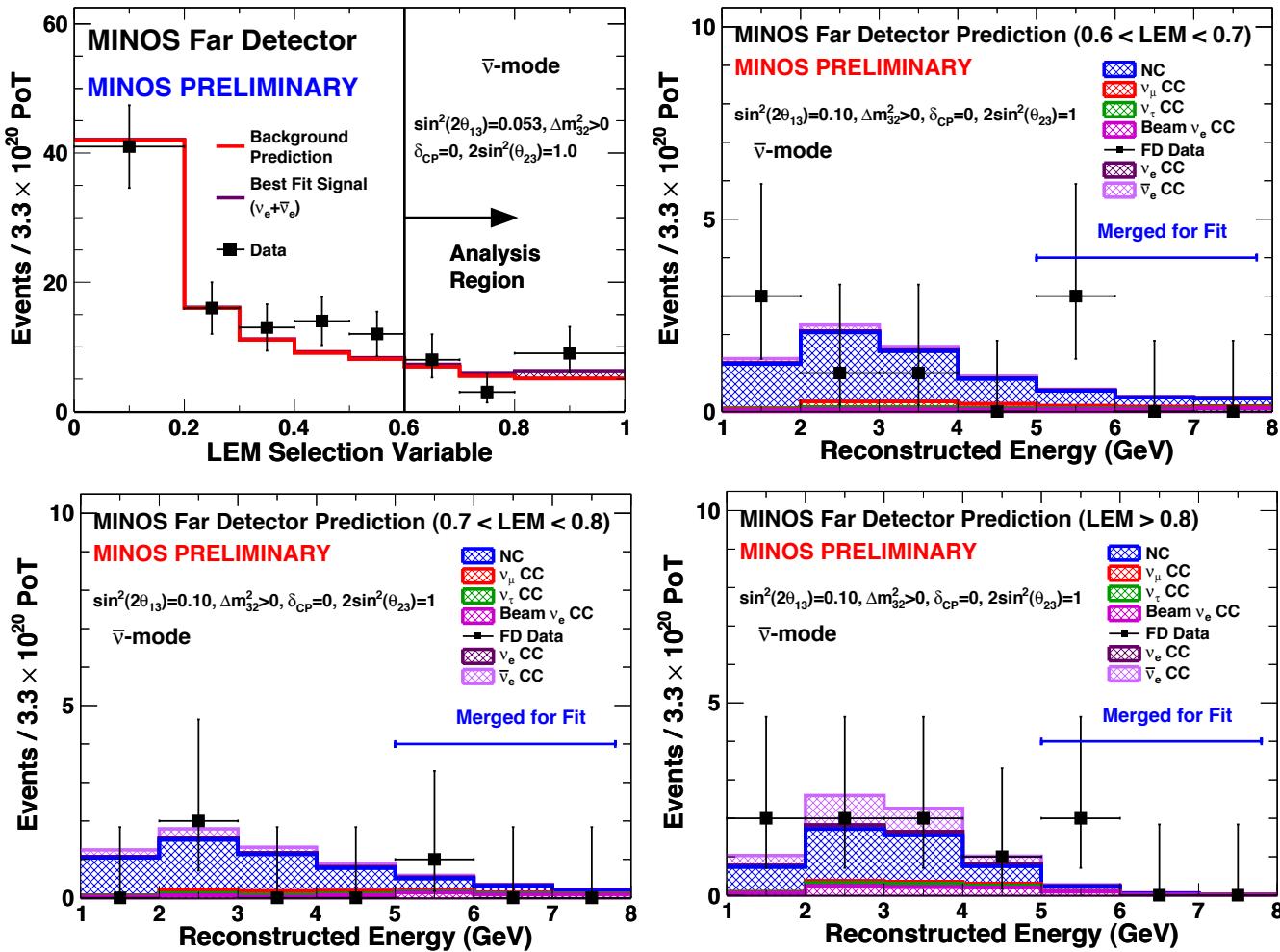




ELECTRON NEUTRINO APPEARANCE: RHC BEAM

In Signal Enhanced Region:

- If $\theta_{13}=0$: 10.5 BG Events
- If $\sin^2(2\theta_{13})=0.1$: +3.1 Events
- Observe: 12 Events



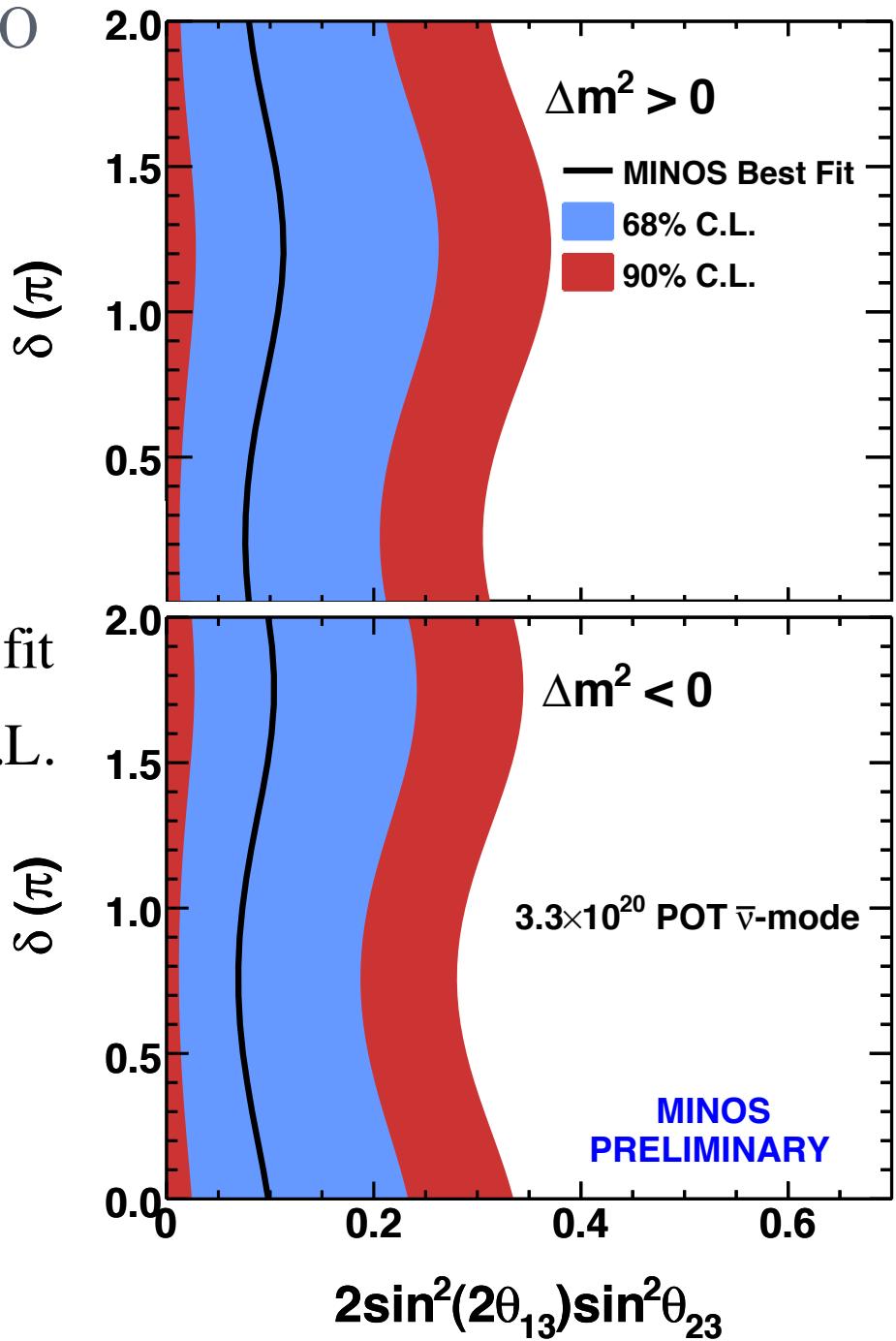
RHC ELECTRON NEUTRINO APPEARANCE CONTOUR

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1$,
normal (inverted) hierarchy:

$\sin^2(2\theta_{13}) = 0.079$ (0.098) at best fit

$\sin^2(2\theta_{13}) < 0.31$ (0.34) at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ excluded at 80%



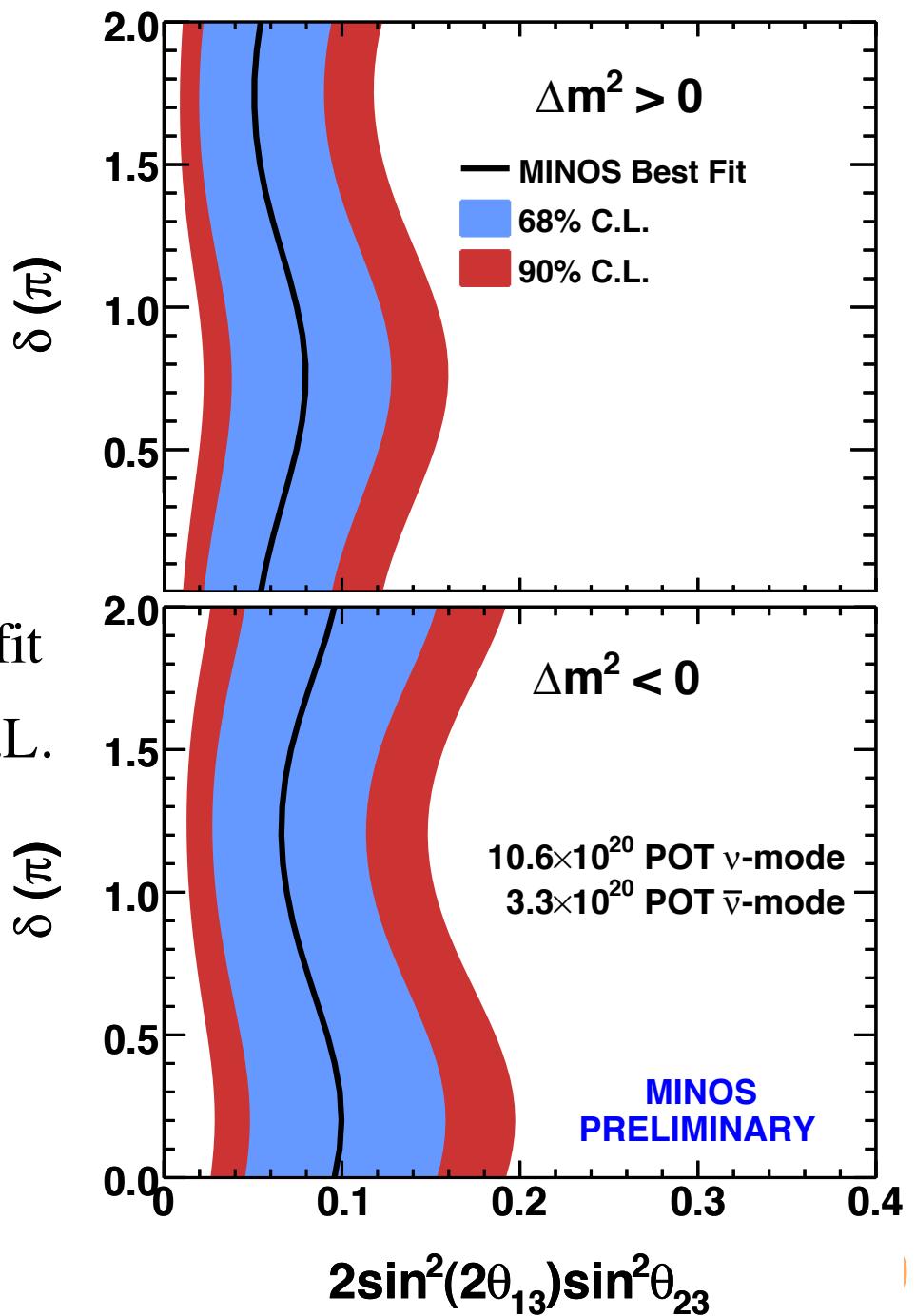
COMBINED ELECTRON NEUTRINO APPEARANCE CONTOUR

for $\delta_{CP} = 0$, $\sin^2(2\theta_{23}) = 1$,
normal (inverted) hierarchy

$\sin^2(2\theta_{13}) = 0.053$ (0.094) at best fit

$0.01 < \sin^2(2\theta_{13}) < 0.12$ at 90% C.L.
(0.03) (0.19)

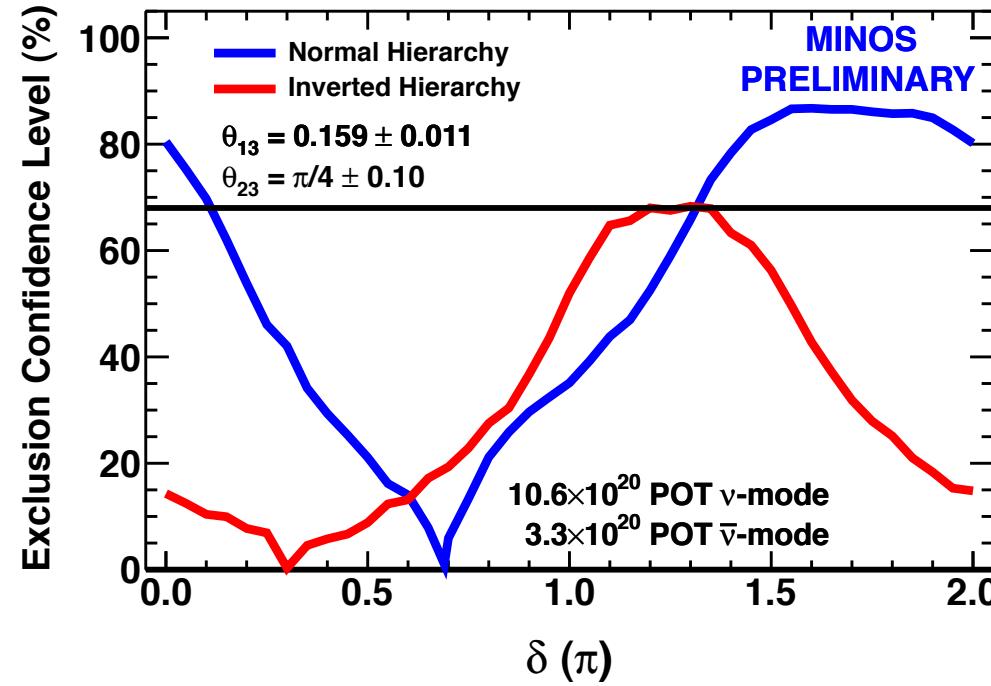
$\sin^2(2\theta_{13}) = 0$ excluded at 96%





DELTA AND THE HIERARCHY

- Using reactor experiments to constrain θ_{13} , our data disfavor some combinations of delta and mass hierarchy



- Sensitivity to hierarchy: In pseudo experiments, we get the hierarchy right 60% of the time (compare to 50% by chance)
- With θ_{13} from reactor experiments, our data slightly favor inverted hierarchy with $-2\Delta \ln L = 0.2$



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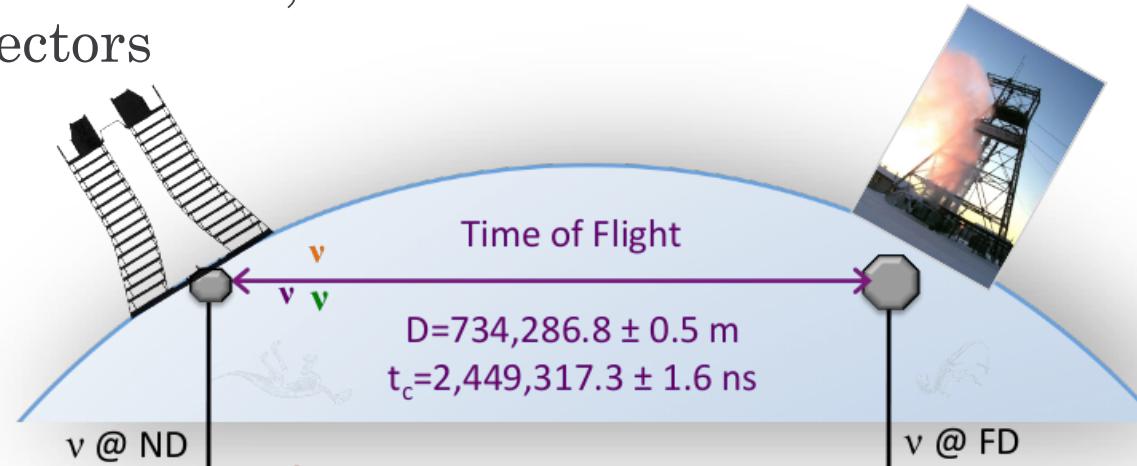
NEUTRINO TIME OF FLIGHT





MEASURING NEUTRINO TIME OF FLIGHT

- Measure the time it takes for NuMI neutrinos to travel the $734,286.8 \pm 0.5$ m between the two MINOS detectors



- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected:
 126 ± 32 (stat.) ± 64 (syst.) ns[†]
- OPERA 2011 also saw neutrinos early:
 57.8 ± 7.8 (stat.) $+8.3/-5.9$ (syst.) ns[‡]
- Update! now neutrinos come late:
 1.6 ± 1.1 (stat.) $+6.1/-3.7$ (syst.) ns^{*}

[†]Phys. Rev. D76 (2007) 072005 [‡]arXiv:1109.4897v2 ^{*}Neutrino 2012



PHASED APPROACH

- Phase I:
 - Update 2007 analysis with a factor of 8 more events
 - Remeasure delays and review systematics
- Phase II:
 - Work done in collaboration with NIST and USNO
 - Collect new data with upgraded GPS and cesium clocks
 - Constant monitoring of optical fiber delays
 - Account for environmental changes, etc.
- Ultimately aim for 2-5 ns accuracy



Phase II equipment provides refined understanding of current timing system systematic uncertainties

MAJOR SYSTEMATIC UNCERTAINTIES

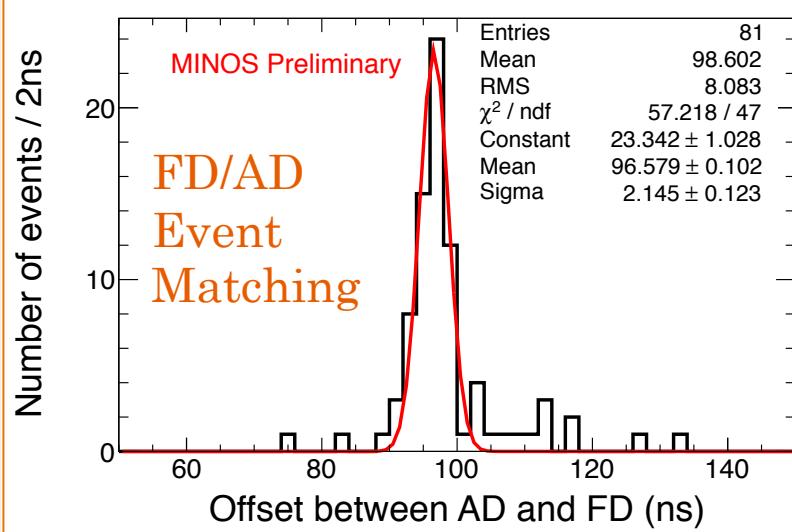
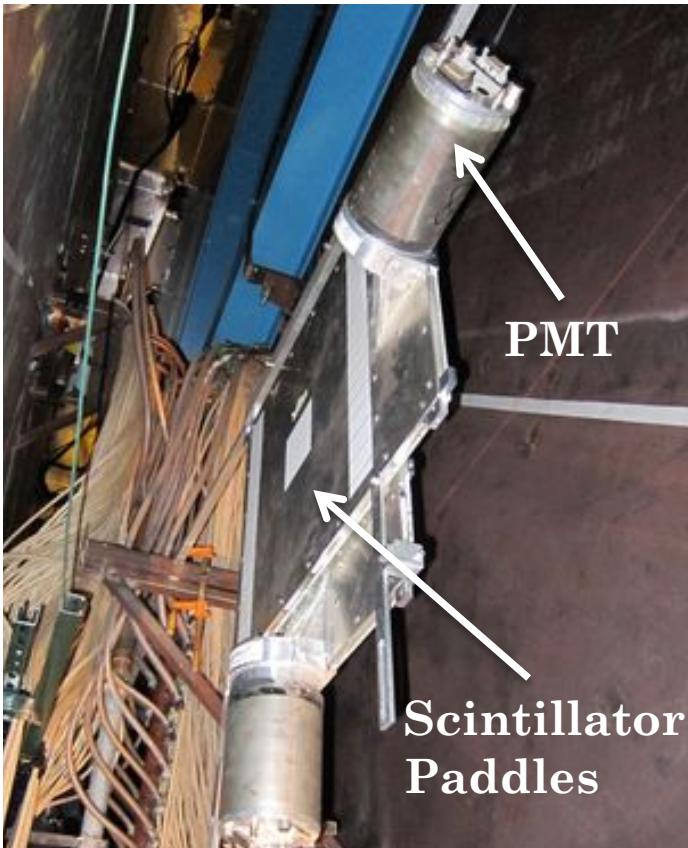


- Arrival times as recorded at each detector must be corrected for (sizeable) cable delays and electronics latencies
- Dominant systematics in first analysis largely mitigated by new, precision measurements of delays

	2007	2012
GPS antenna to ND cable delay	1275 ± 29 ns	1309 ± 1 ns
GPS antenna to FD cable delay	5140 ± 46 ns	5098 ± 2 ns



THE AUXILIARY DETECTORS (AD)

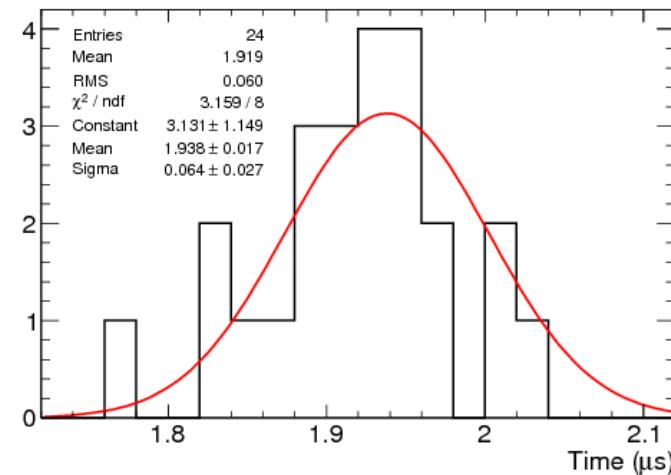
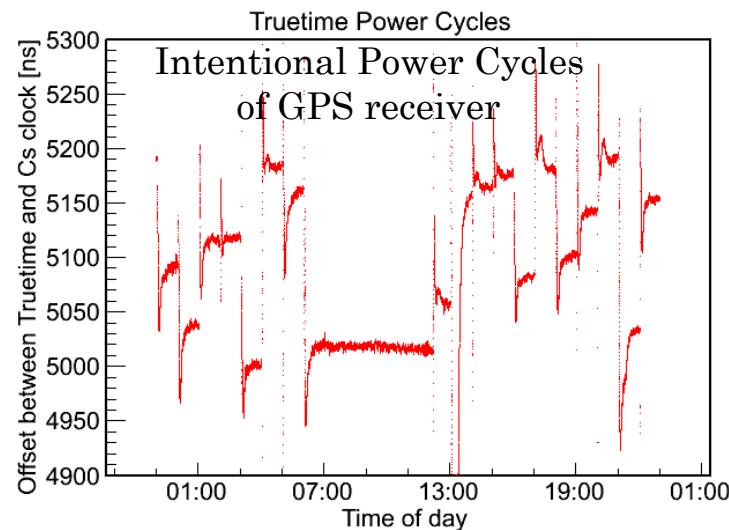


- Scintillator paddles with PMTs
- Two independent readouts
- Match muons in MINOS detectors with muons crossing AD
- Difference in matched event times recorded in each device measures latency in neutrino detector relative to AD latency
- Compare Near to Far Detector latencies, AD latency cancels
- Relative latency 24 ± 1 ns

TIMING SYSTEM STABILITY



- Recent measurements of the MINOS GPS receivers against cesium clocks reveal GPS time discontinuities after power cycles



- Stable to within 10ns between power cycles
- 60 ns RMS jitter upon power cycles
- Data recorded over past 7 years include 27 power cycles
 - Do not know new GPS offset after power cycle, but we do know when power cycles occurred
 - Analysis approach: average over many power cycles cancels the effect of this random jitter



ADDITIONAL SYSTEMATIC UNCERTAINTIES



- Calibrating ND/FD GPS receivers
 - Traveling USNO TWSTT-capable GPS receiver visited FNAL and Soudan
 - Two receivers exchange timing synchronization information via the satellite
 - Comparison of ND/FD GPS time to traveling receiver reveals mean time offset between ND and FD: 22 ± 21 ns
- ND Spill trigger delay
 - Delay between beam extraction signal and issue of ND beam trigger is bimodal
 - Incur systematic uncertainty of 19 ns

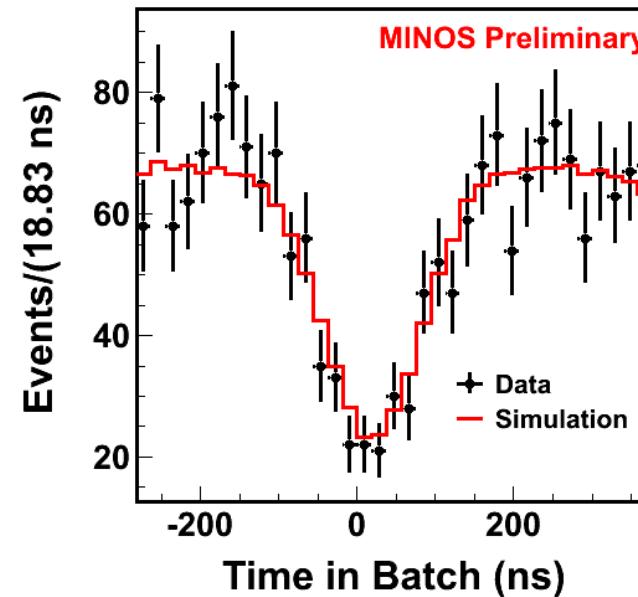
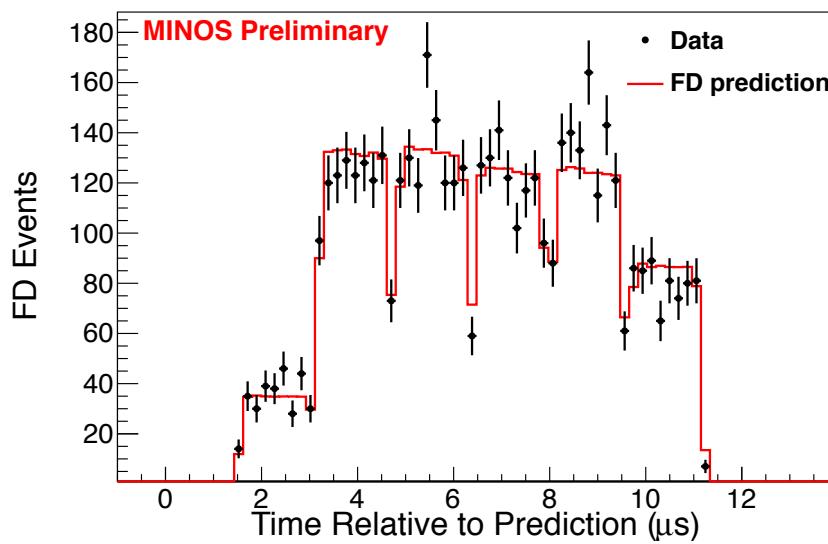
Total Systematic Error: 29 ns



THE ANALYSES

- NuMI neutrinos span a 10 us spill
 - spill subdivided into 1.619 us batches
 - 95 ns gap between batches

Two Analysis Approaches:



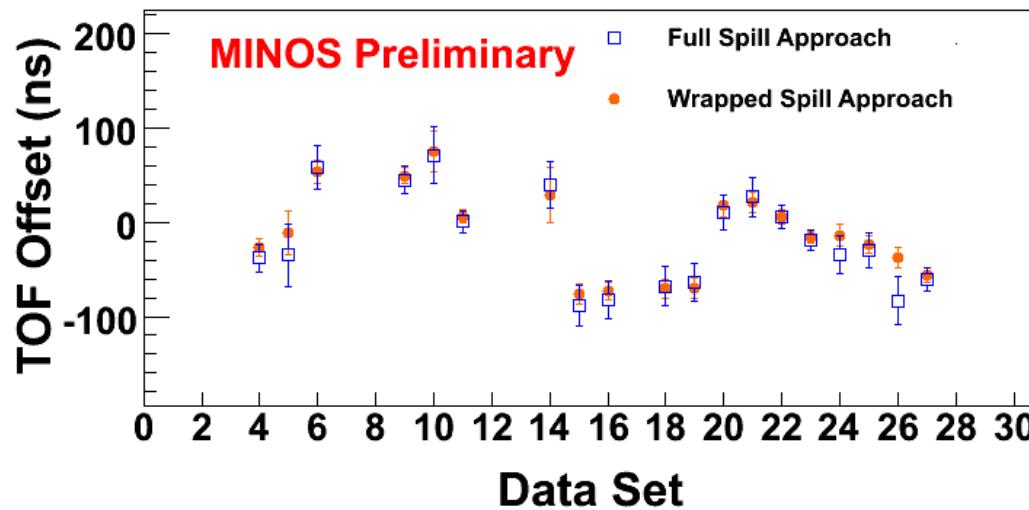
- Full spill approach
 - event time within spill in ND predicts FD distribution
 - Vary time of flight to match data

- Wrapped Spill approach
 - Measure event time within batch
 - Find batch gap time in each detector
 - Subtract for time of flight



COMPARING THE APPROACHES

- Divide data set into subsets between timing system power cycles



- Individual results change with power cycles
- Average over individual results for final TOF result
- Error on mean taken as the statistical error on the result



RESULTS

- In Full Spill approach, neutrinos arrive earlier than expected by:
$$18 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns}$$
- In Wrapped Spill approach, neutrinos arrive earlier than expected by:
$$11 \pm 11 \text{ (stat.)} \pm 29 \text{ (syst.)} \text{ ns}$$
- The two approaches give results consistent with one another
- The two results are consistent with neutrinos traveling at the speed of light
- Analysis with improved timing system pending
 - ~200 contained CC events collected with new timing system operational

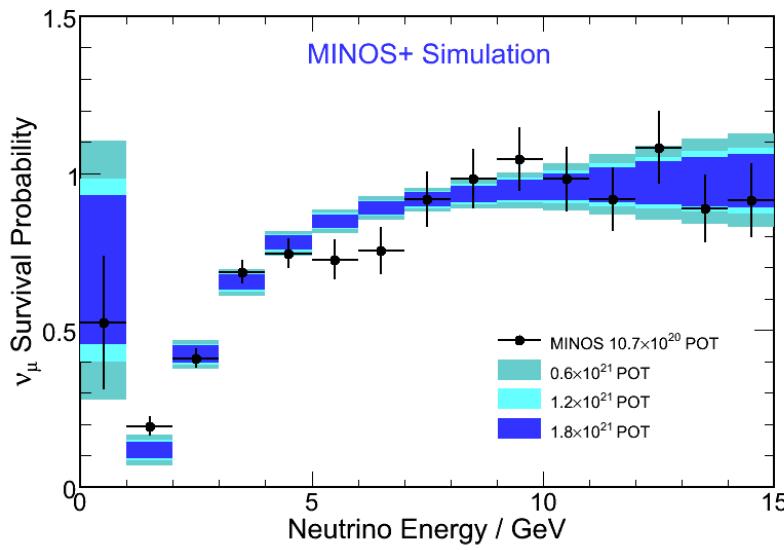
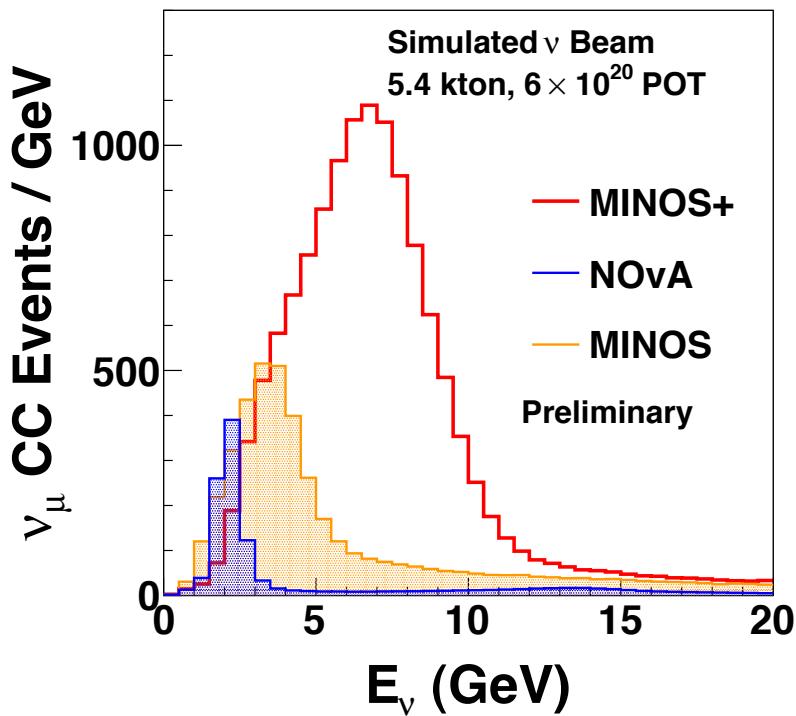


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MINOS+



MINOS+



- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- But we get a lot of events!
 - ~4000 muon neutrino CC events per year expected at FD
 - ~80 tau neutrino CC events (with a lot of background)
- Unique test of oscillation paradigm with sensitivity to exotic signals



CONCLUSIONS

- Analysis of muon neutrino disappearance using Beam + Atmospheric samples finds:

$$|\Delta m^2| = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ (90% C.L.)}$$

$$|\Delta \bar{m}^2| = 2.48_{-0.27}^{+0.22} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90% C.L.)}$$

- Search for electron neutrino appearance finds:

$$0.01(0.03) < \sin^2(2\theta_{13}) < 0.12(0.19) \text{ at 90% C.L.}$$

for $\delta_{CP} = 0$, $\sin^2(2\theta_{23}) = 1$, normal (inverted) hierarchy

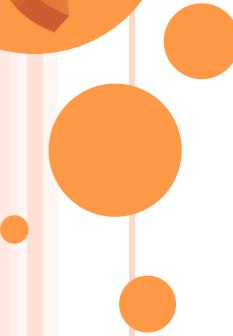
$$\sin^2(2\theta_{13}) = 0 \text{ excluded at 96\%}$$

- MINOS measures neutrinos travel at a speed consistent with the speed of light
- Stay tuned! MINOS+ will continue to provide exciting physics in the years to come.



ACKNOWLEDGEMENTS

- On behalf of the MINOS collaboration, we would like to express our gratitude to the many Fermilab groups (Accelerator Division, Business Services, Laboratory Services, ES&H, Computing Division) for their technical expertise and support in the design, construction, installation, and operation of the experiment.
- Particular thanks to the Minnesota DNR and the crew of the Soudan Underground Laboratory to whom we owe our impressive FD uptime.
- We would also like to recognize NIST and USNO for their timing expertise and advice.
- We would also like to acknowledge the support from DOE, UK STFC, NSF, the State and University of Minnesota, the University of Athens, and Brazil's FAPESP, CNPq and CAPES

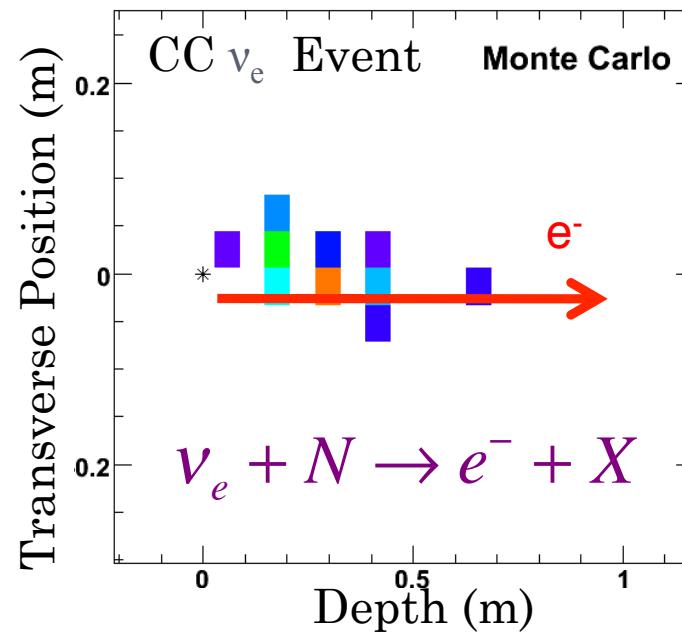
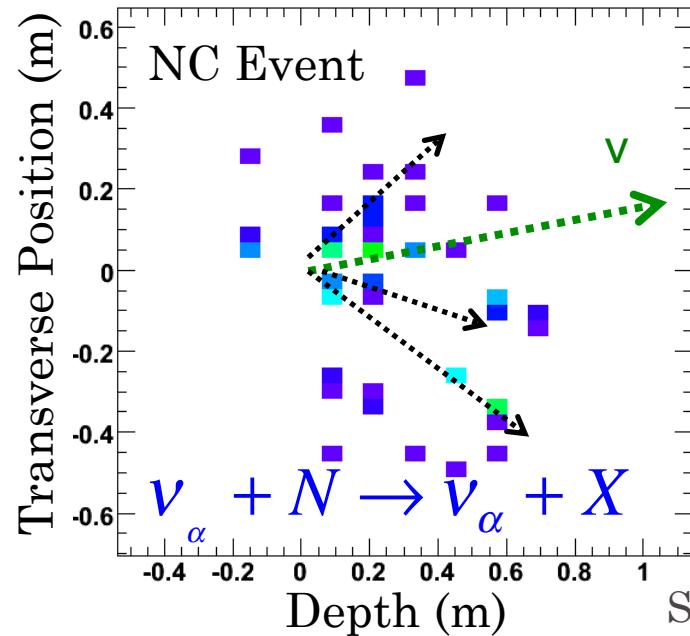
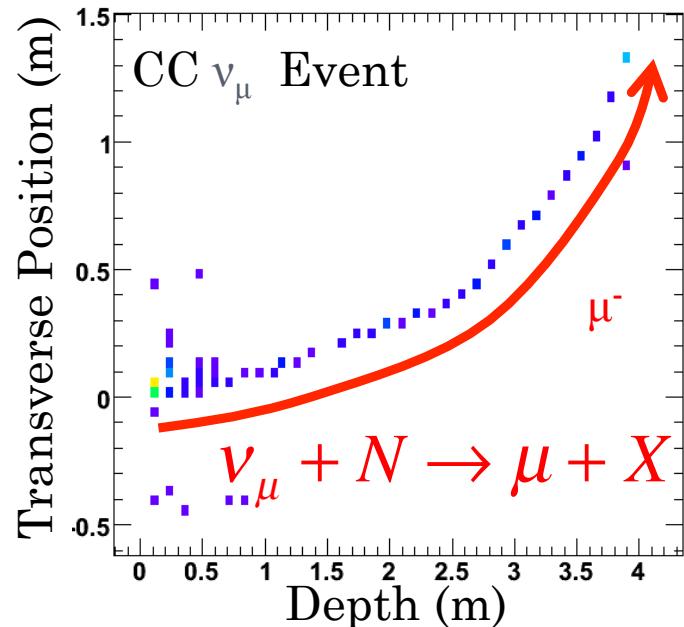


BACKUP SLIDES





EVENTS IN MINOS

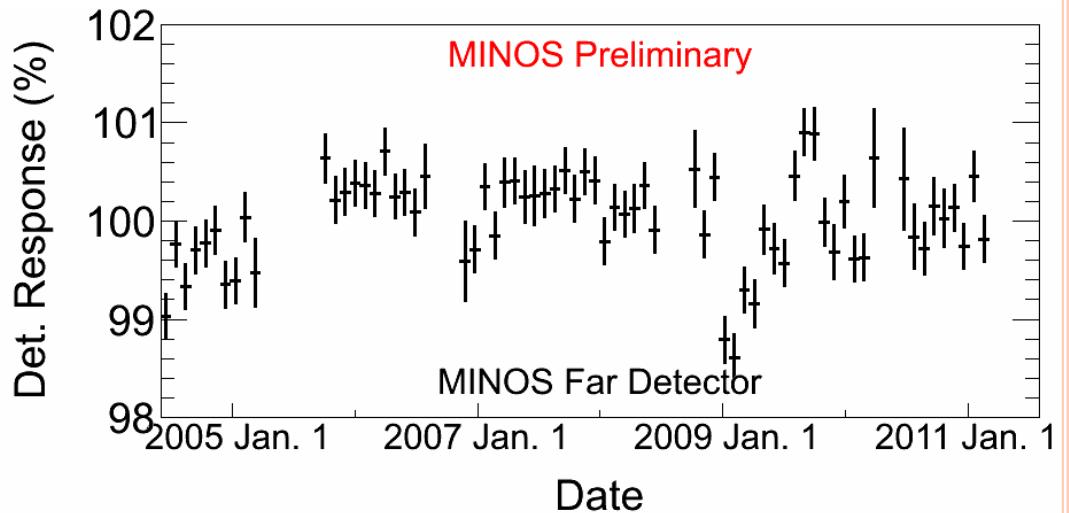
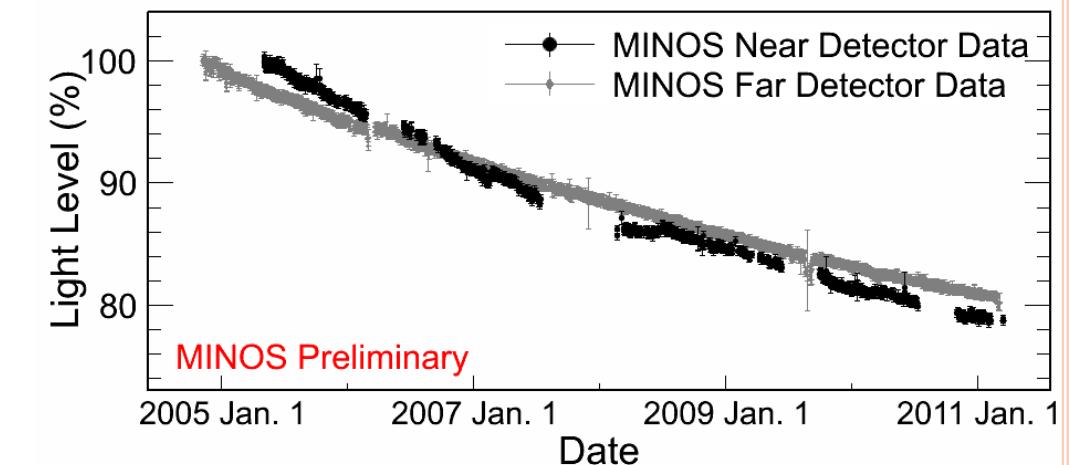


- ν_μ Charged Current events:
 - energy from sum of muon energy (range or curvature) and shower energy
- NC or ν_e :
 - energy from calorimetric response

Simulated Events

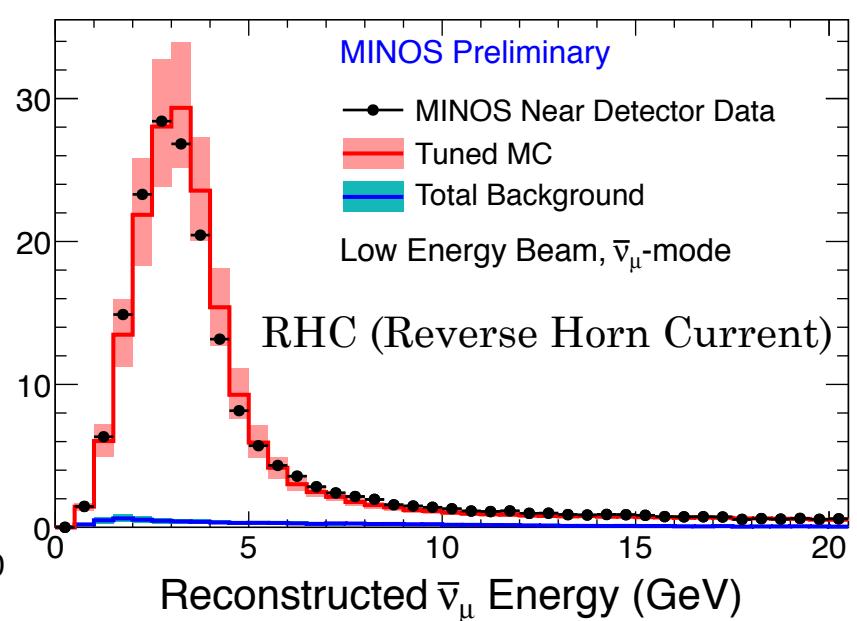
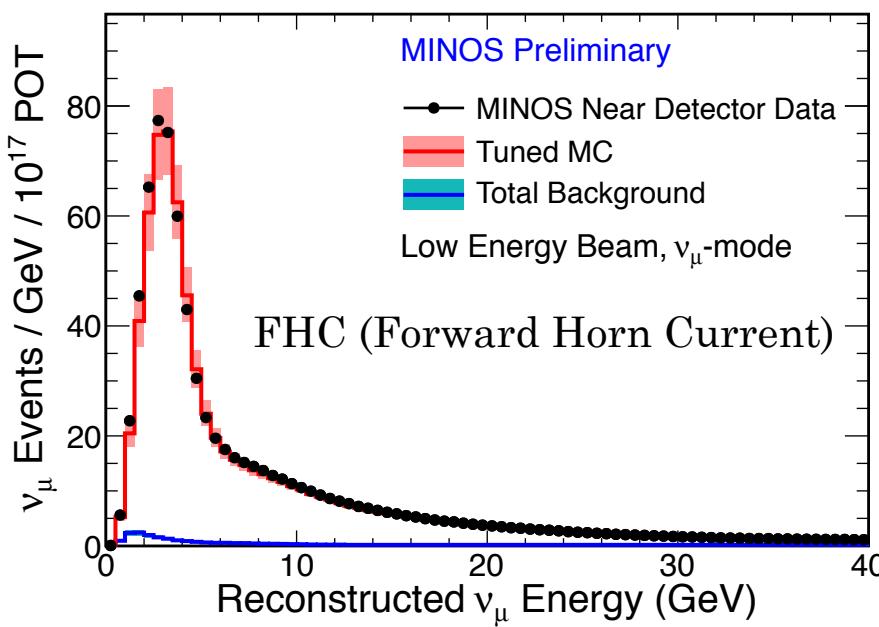
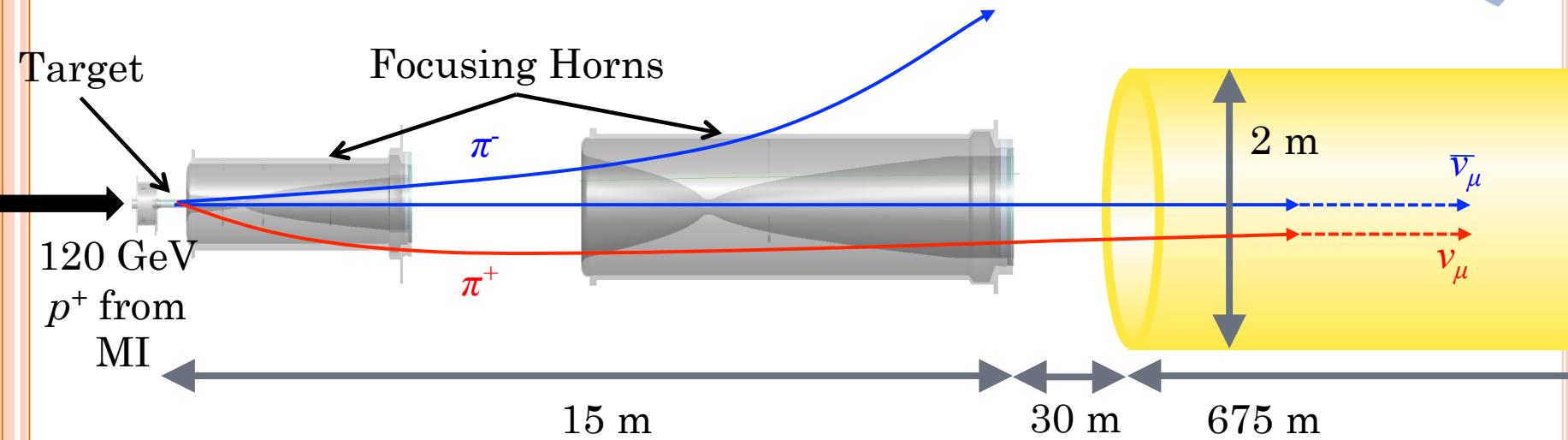
DETECTOR STABILITY

Far Detector live
for 97% of Beam
Exposure



	Near	Far
Gains Increase/year	2.5%	1.8%
Light Level Decrease/year	3.5%	3.0%
Overall Stability (after calibration)	0.5%	1.5%

MAKING A NEUTRINO BEAM





DISAPPEARANCE RESULTS

Beam Neutrinos:

$$|\Delta m^2| = 2.41_{-0.10}^{+0.11} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.94_{-0.05}^{+0.04}$$

RHC Beam Antineutrinos:

$$|\Delta \bar{m}^2| = 2.64_{-0.27}^{+0.28} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.95_{-0.10}^{+0.09}$$

$$\sin^2(2\bar{\theta}) > 0.78 \text{ (90% C.L.)}$$

All Beam Antineutrinos:

$$|\Delta \bar{m}^2| = 2.60_{-0.23}^{+0.28} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.97_{-0.10}^{+0.03}$$

$$\sin^2(2\bar{\theta}) > 0.80 \text{ (90% C.L.)}$$

Beam + Atmospherics, 2 parameters:

$$|\Delta m^2| = 2.39_{-0.10}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 0.96_{-0.04}^{+0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ (90% C.L.)}$$

Beam + Atmospherics, 4 parameters:

$$|\Delta \bar{m}^2| = 2.48_{-0.27}^{+0.22} \times 10^{-3} \text{ eV}^2$$

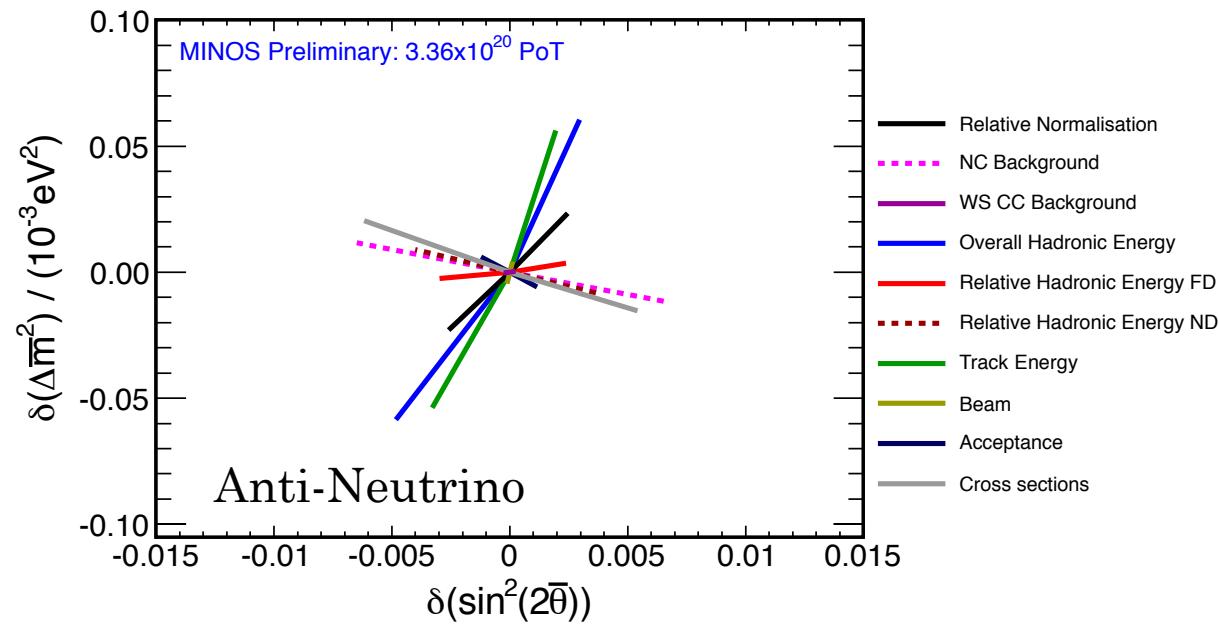
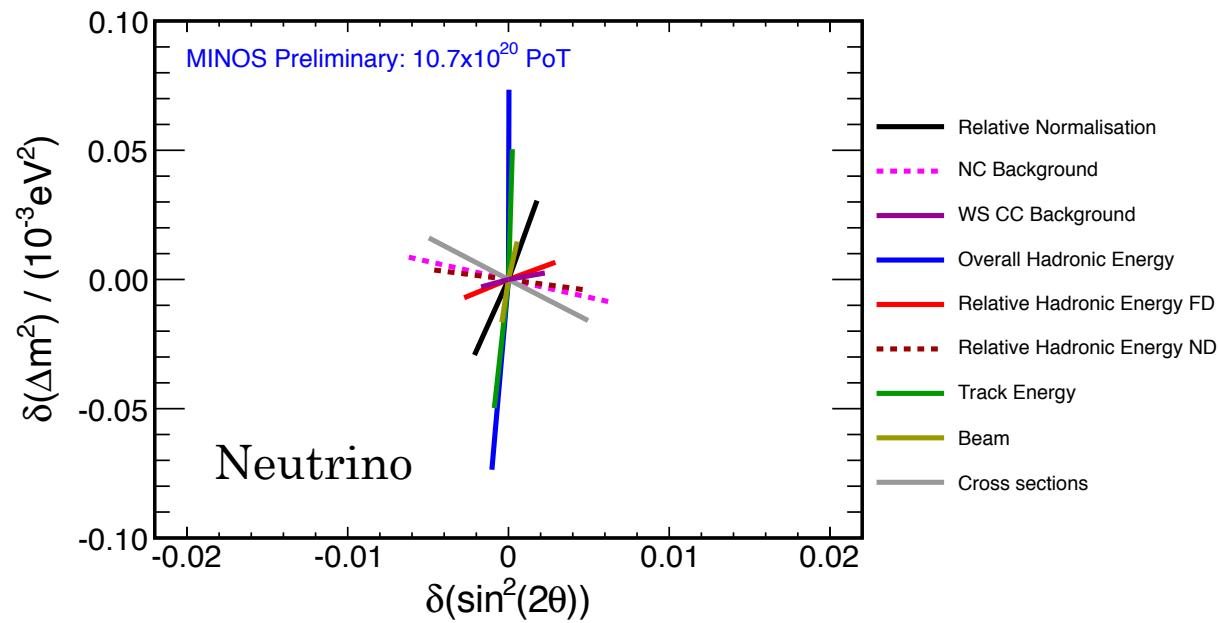
$$\sin^2(2\bar{\theta}) = 0.97_{-0.08}^{+0.03}$$

$$\sin^2(2\bar{\theta}) > 0.83 \text{ (90% C.L.)}$$

$$|\Delta \bar{m}^2| - |\Delta m^2| = 1.0_{-2.8}^{+2.4} \times 10^{-4} \text{ eV}^2$$



MUON NEUTRINO SYSTEMATICS



ATMOSPHERIC NEUTRINOS



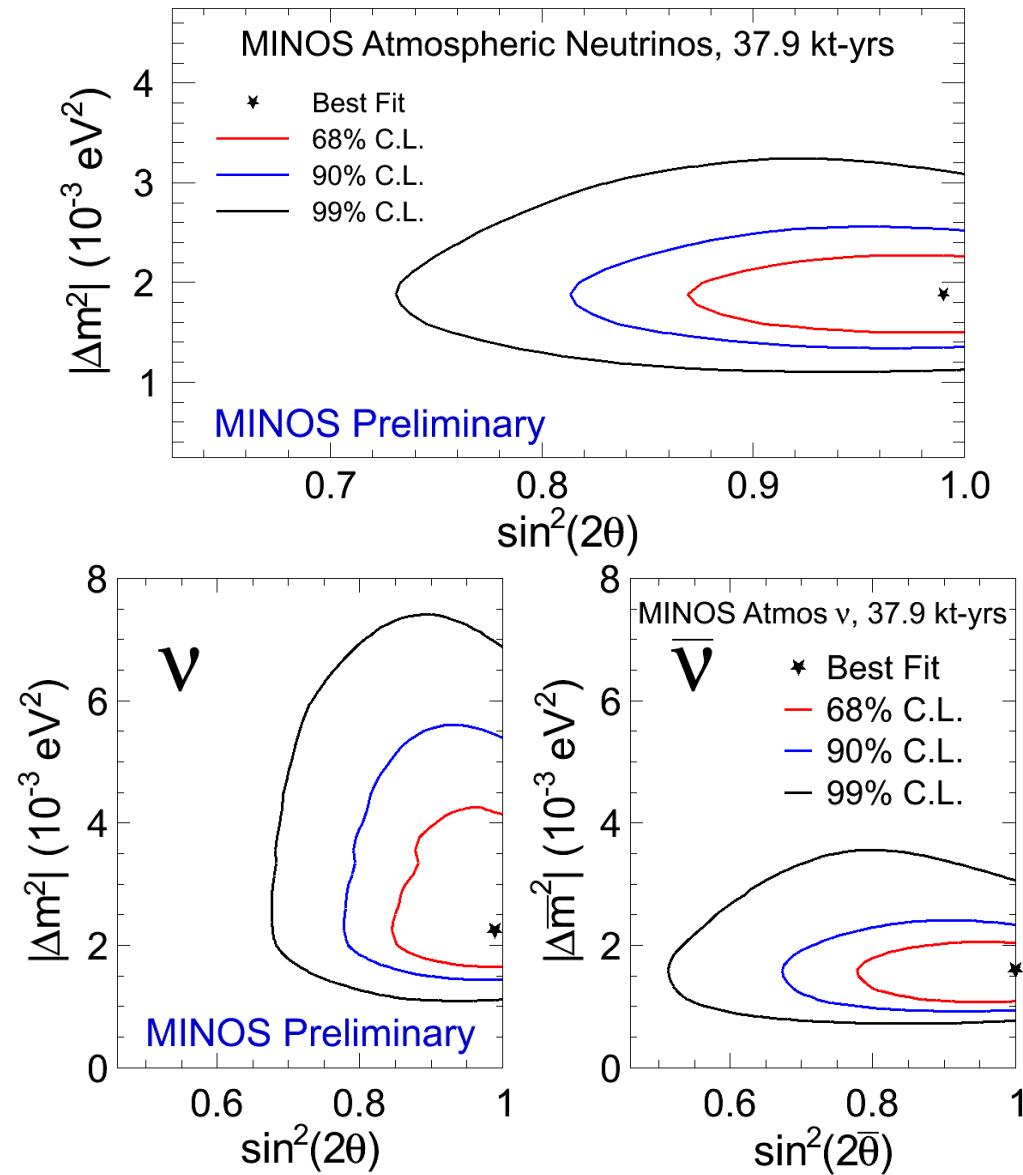
- Without charge sign selection:

$$|\Delta m^2| = 1.9^{+0.4}_{-0.4} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) > 0.86 \\ (90\% \text{ C.L.})$$

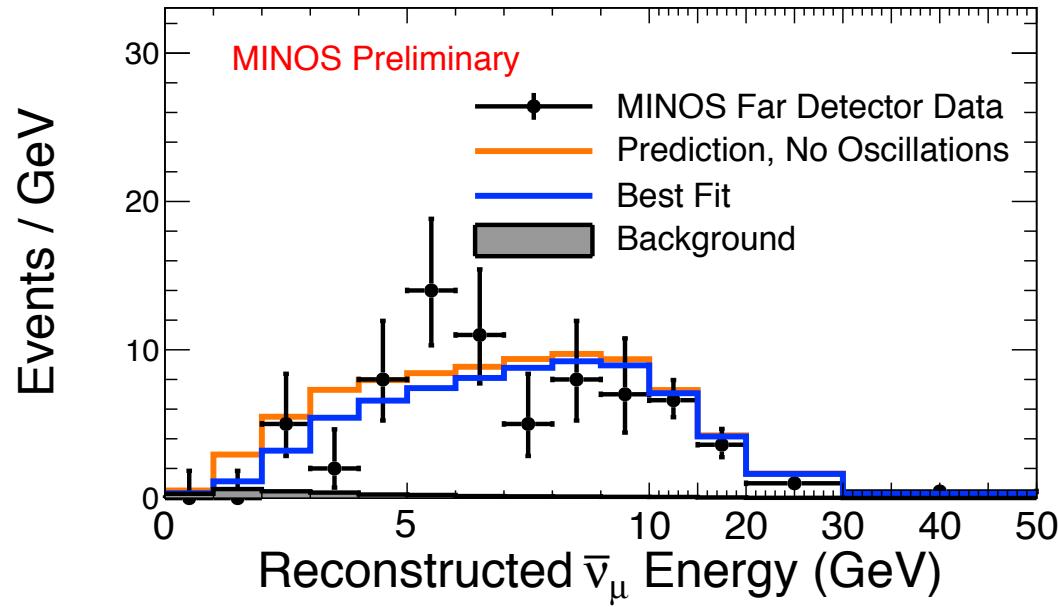
- Separating by charge:

$$|\Delta m^2| - |\Delta \bar{m}^2| = 0.6^{+2.4}_{-0.8} \times 10^{-3} \text{ eV}^2 \\ (90\% \text{ C.L.})$$





ADDING MORE ANTINEUTRINOS



- Antineutrino component of FHC beam
 - most events at energies above the oscillation dip
 - extra events help constrain antineutrino fit parameters



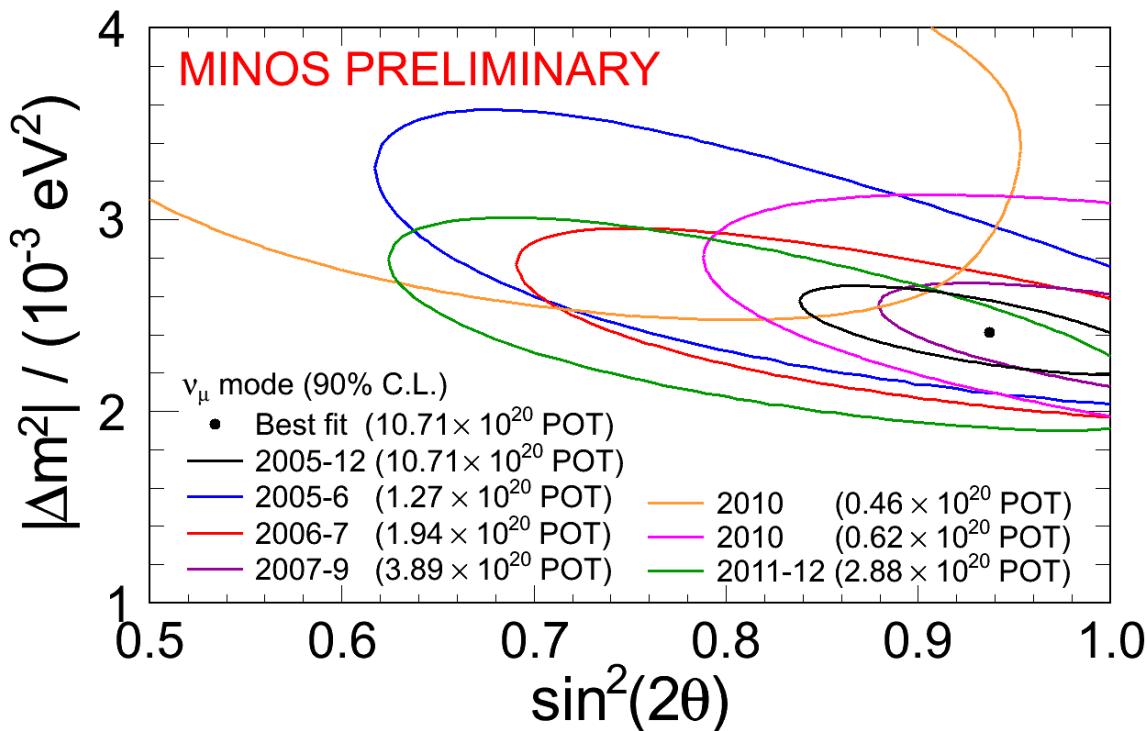
STATISTICS

Beam Events	No Oscillations	Observed
FHC Neutrinos	3564	2894
FHC Antineutrinos	224	188
RHC Antineutrinos	312	226

Atmospheric	No Oscillations	Observed
Contained CC	1100	905
Rock Vertex	570	466
Showers	727	701



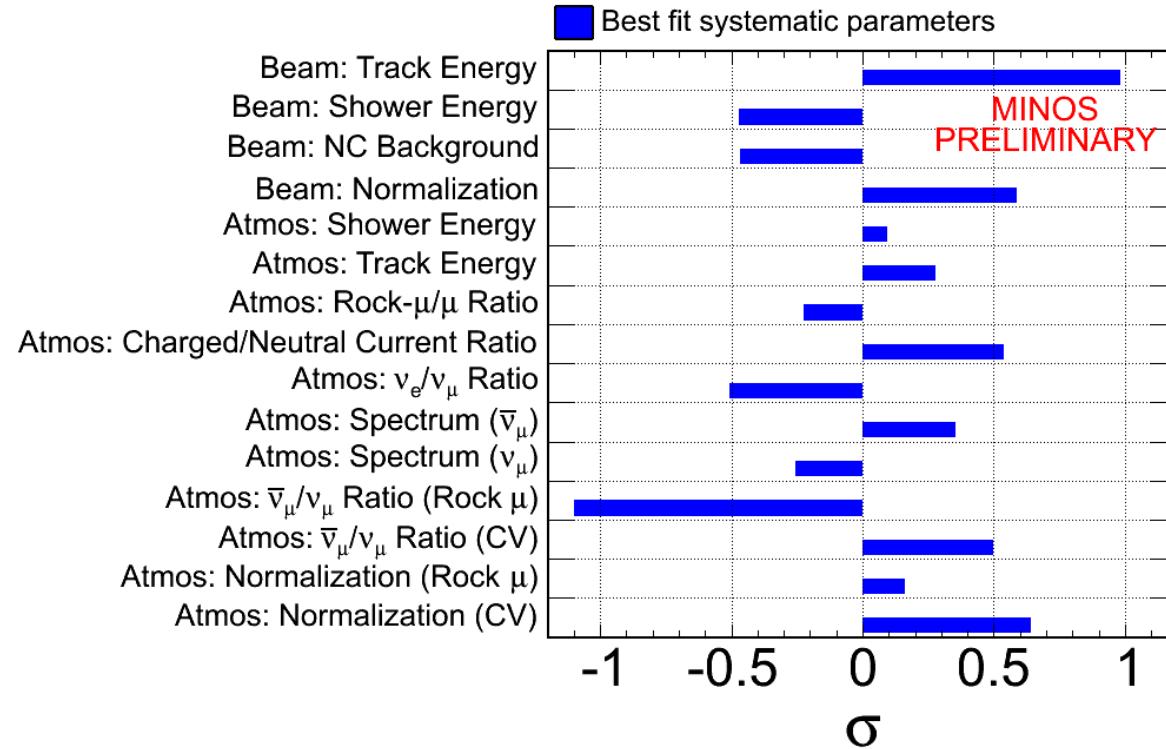
CONTOUR EVOLUTION



Run	I	pHE	II	III	V	VI	X	All
POT ($\times 10^{20}$)	1.27	0.15	1.94	3.89	0.46	0.62	2.88	10.71
Events	317	119	509	1034	113	154	648	2894
Δm^2 ($\times 10^{-3} \text{ eV}^2$)	2.62	2.52	2.38	2.37	3.66	2.56	2.41	2.41
$\sin^2(2\theta)$	0.89	1.00	0.94	1.00	0.73	1.00	0.84	0.94



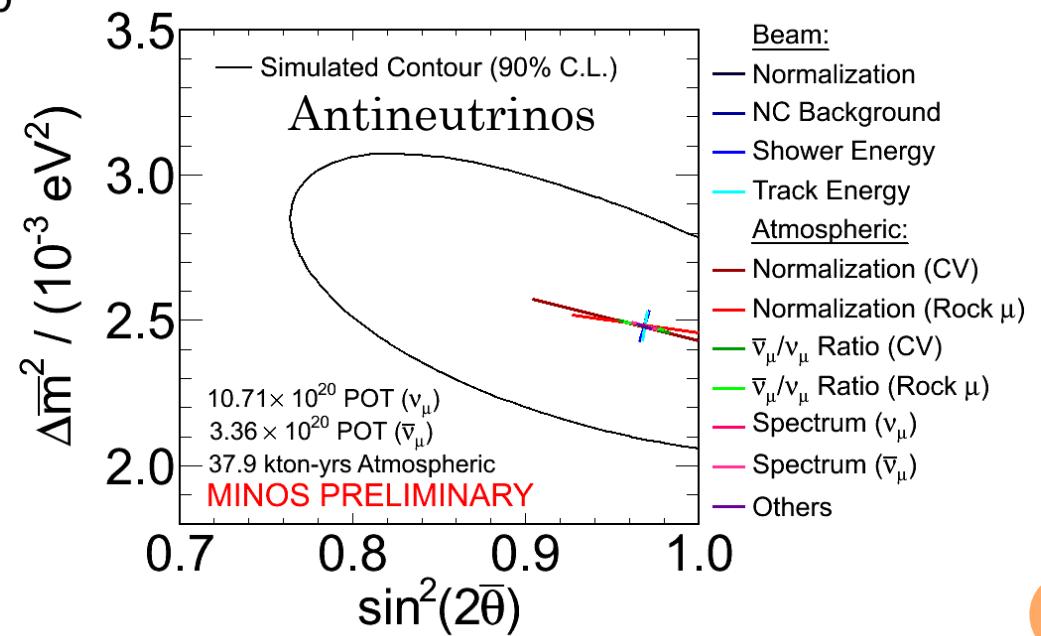
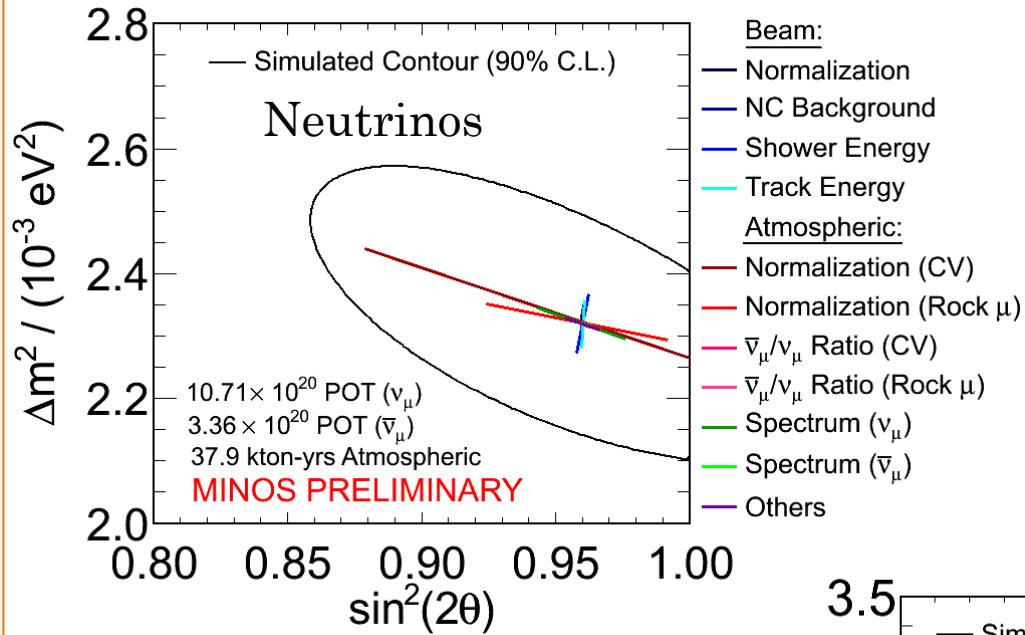
THE METHOD



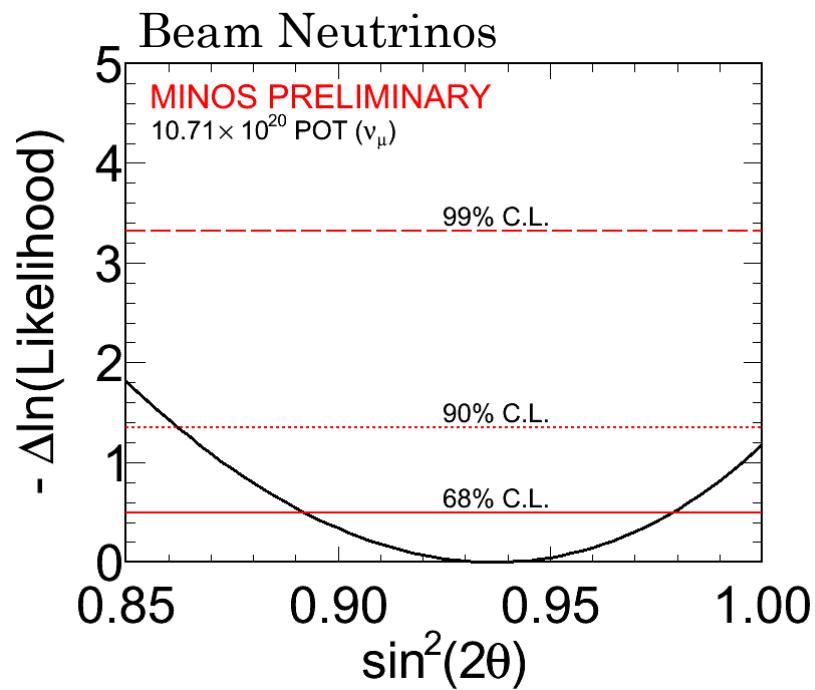
- 15 systematic effects included in fit as nuisance parameters
- Most systematic parameters fit within 1 sigma of their nominal value



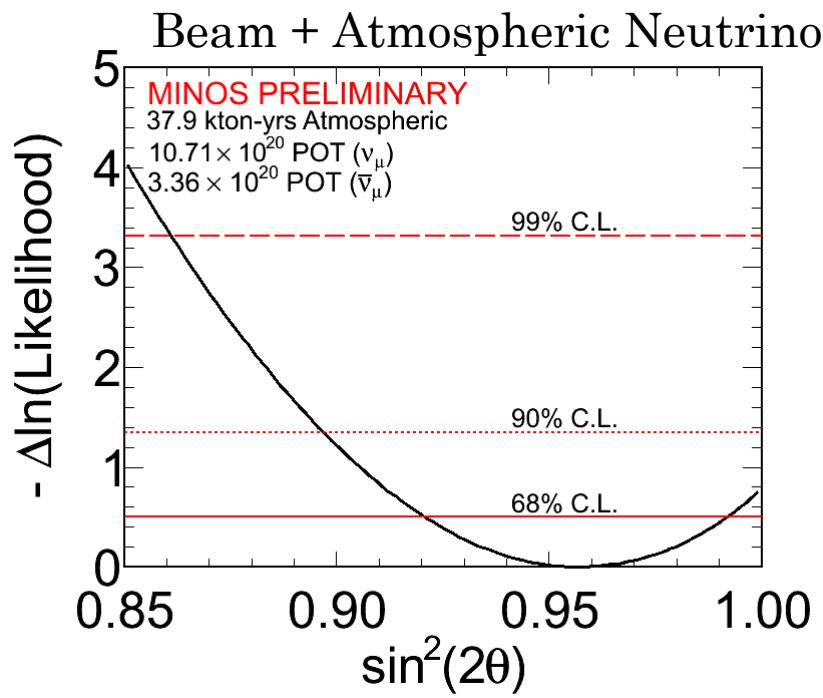
COMBINED FIT SYSTEMATICS



MAXIMAL MIXING



- maximal mixing allowed at 88% C.L.

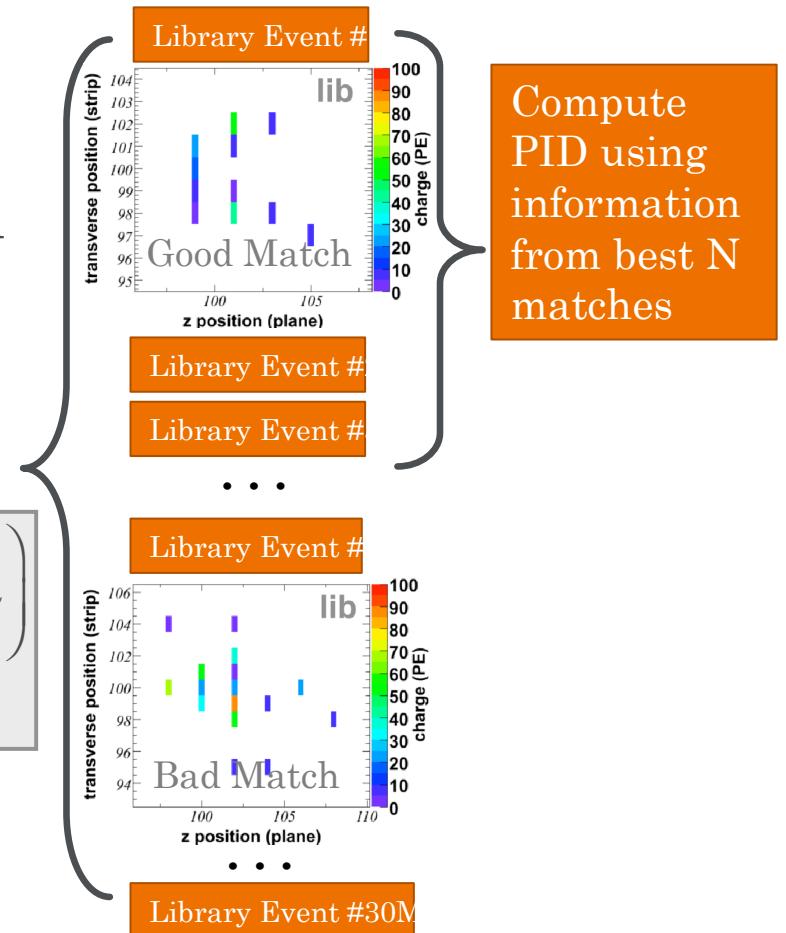
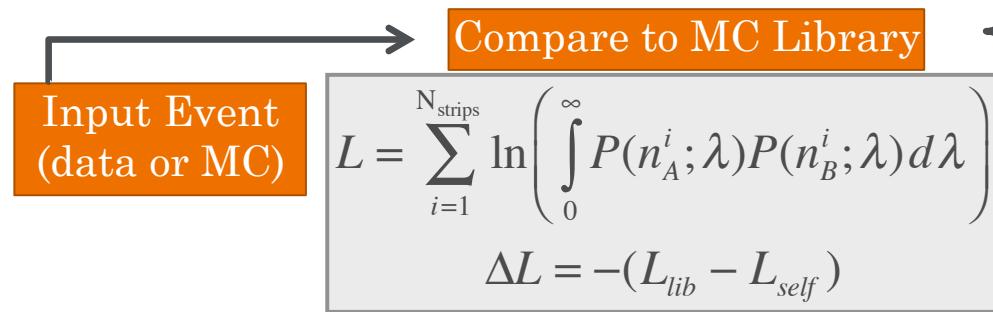


- maximal mixing allowed at 79% C.L.



LOOKING FOR ELECTRON-NEUTRINOS

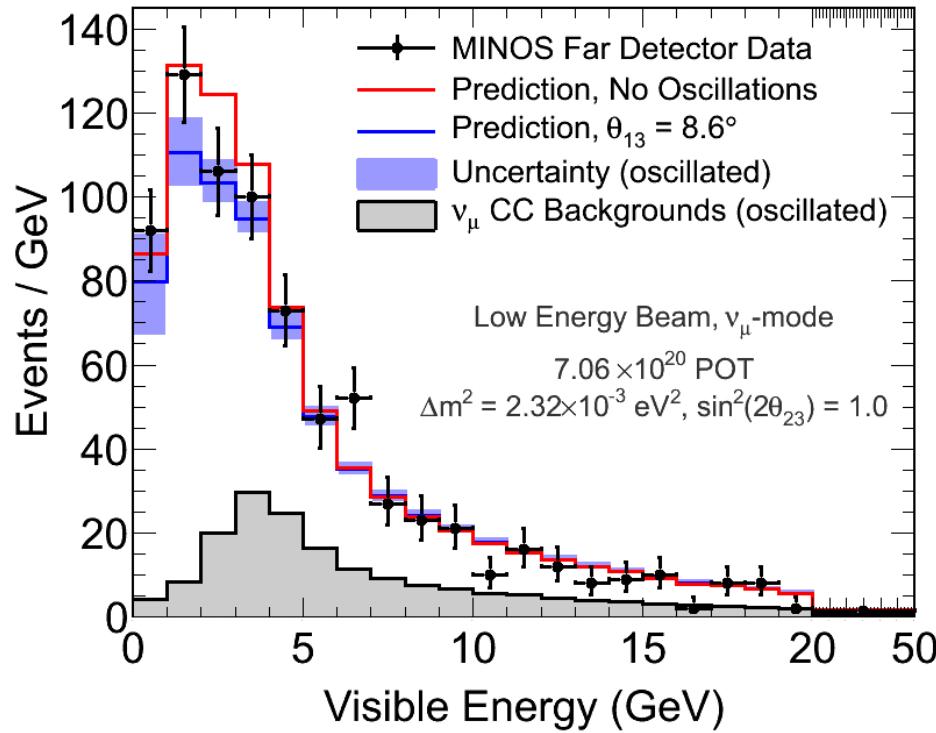
- Compare candidate events to a library of simulated signal and background events
- Discriminating variables formed using information from 50 best matches



- Use ND to determine expected background
- Fit FD in bins of event discrimination variable and energy



NEUTRAL CURRENTS IN THE FAR DETECTOR



- Expect: 757 events
- Observe: 802 events
- No deficit of NC events

$$R = \frac{N_{\text{data}} - BG}{S_{NC}}$$

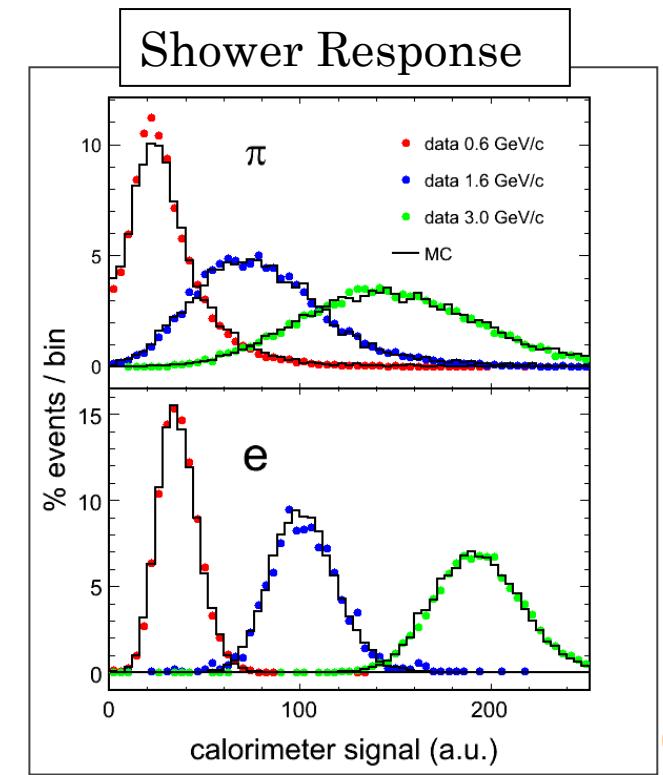
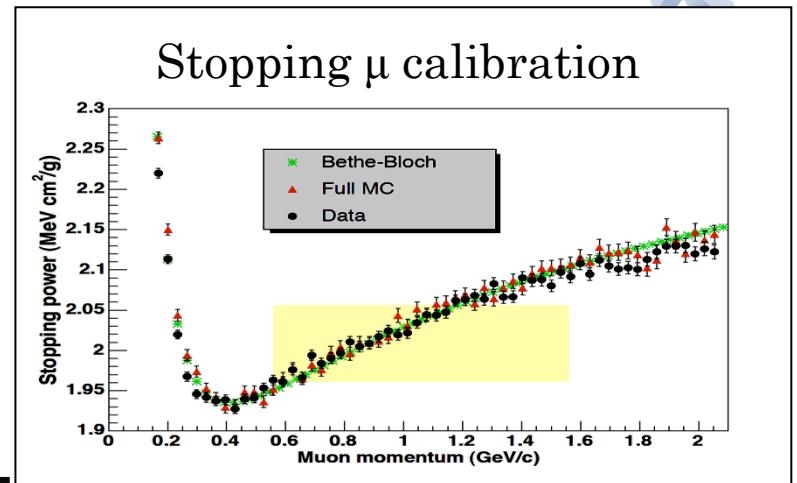
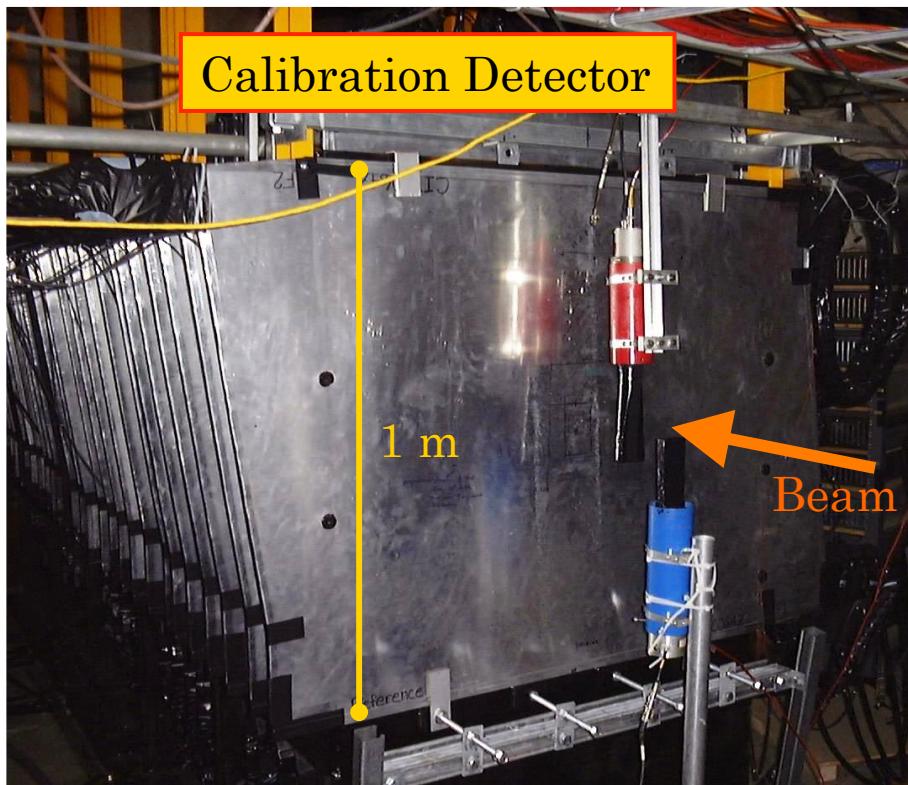
$$1.06 \pm 0.06 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

- New results later this summer will include more data, antineutrinos, effects of oscillations in ND



CALIBRATION DETECTOR

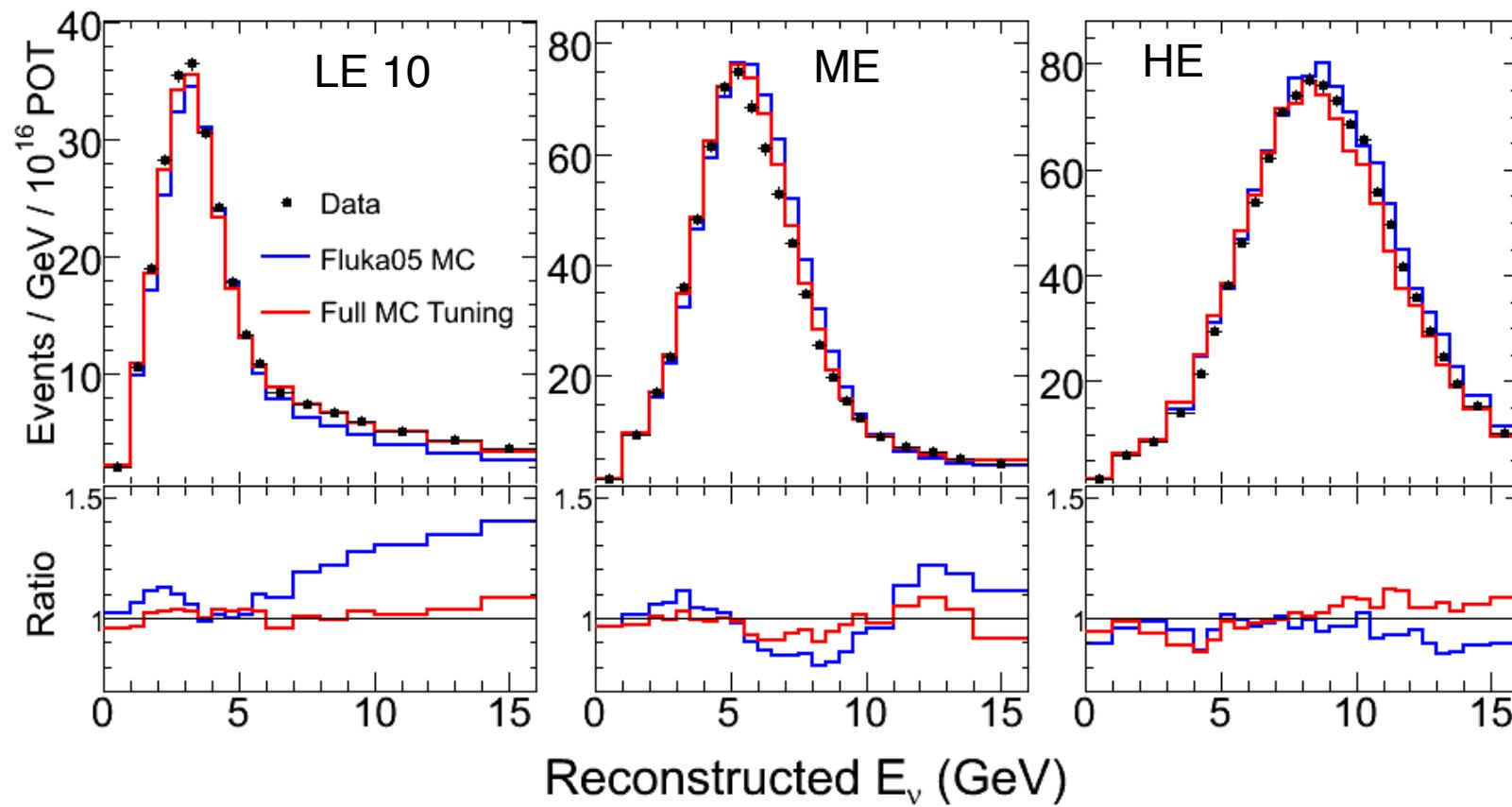
- Dedicated calibration module run in test beams at CERN, 2001-2004
- Characterize response of detector to e, pi, p



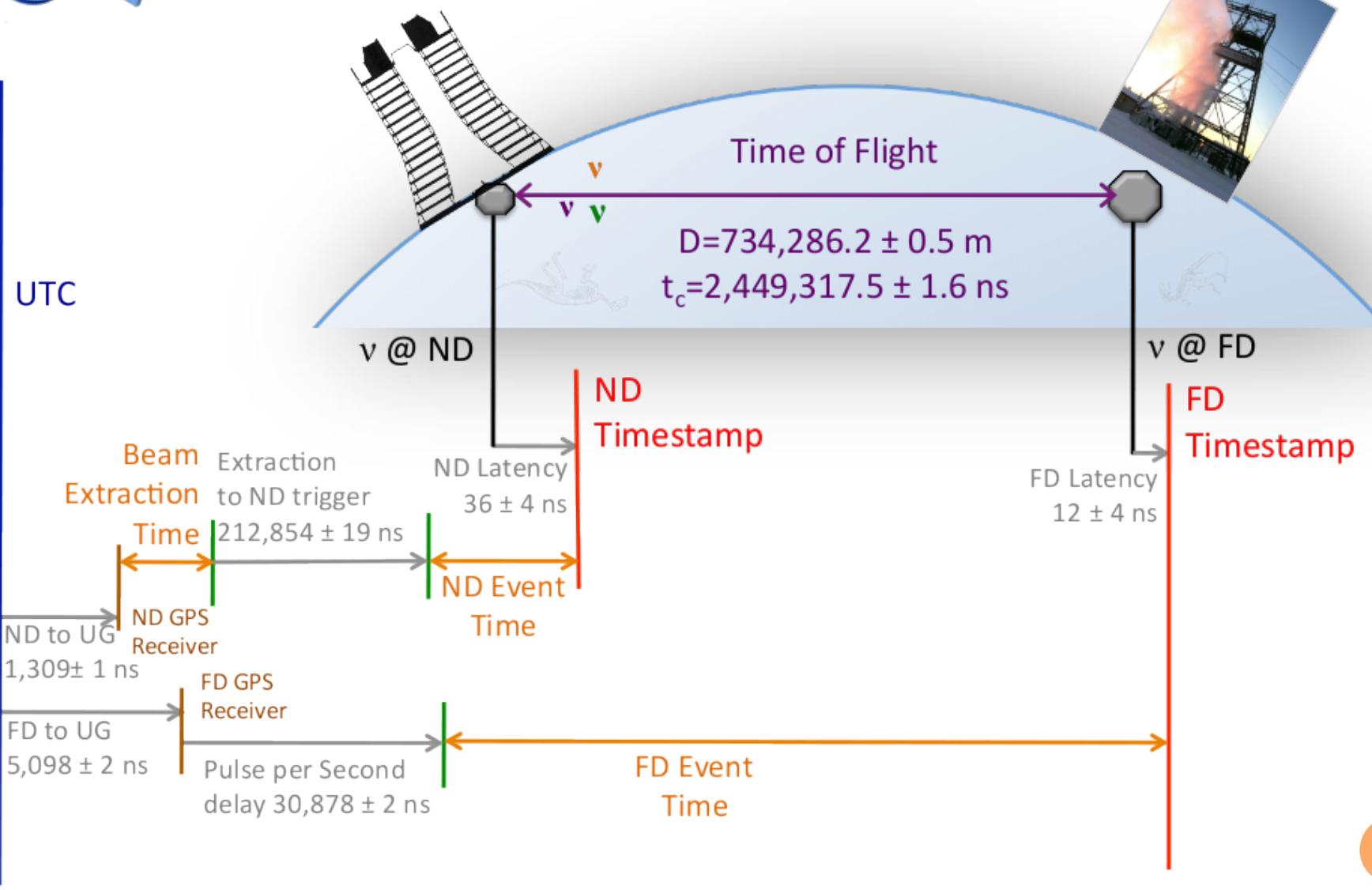


NEUTRINO SPECTRUM

- Use flexibility of beam line to constrain hadron production, reduce uncertainties due to neutrino flux



TIMING DIAGRAM



UPDATES FROM NEUTRINO2012

Photo of S. Bertolucci talk
(courtesy A. Sousa)

The XXV International Conference on Neutrino Physics and Astrophysics **NEUTRINO2012**

To summarize

- All experiments consistent with no measurable deviation from the speed of light for neutrinos:
 - Borexino: $\delta t = 2.7 \pm 1.2$ (stat) ± 3 (sys) ns
 - ICARUS: $\delta t = 5.1 \pm 1.1$ (stat) ± 5.5 (sys) ns
 - LVD: $\delta t = 2.9 \pm 0.6$ (stat) ± 3 (sys) ns
 - OPERA: $\delta t = 1.6 \pm 1.1$ (stat) [+ 6.1, -3.7] (sys) ns
- Very preliminary analyses, more refinements to be expected soon
- A paradigmatic example of collaboration and competition!

MINOS+



- Using complementary information from Bugey, MINOS+ can almost rule out the low mass LSND region

